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A simplified energy performance assessment method supporting system design and fed by EU product policy data : application to heating systems in buildings

Maria Calero Pastor

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THÈSE

Pour obtenir le grade de

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COMMUNAUTÉ UNIVERSITÉ GRENOBLE ALPES

Spécialité : GI : Génie Industriel : conception and production

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Présentée par

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Thèse dirigée par **Daniel BRISSAUD** Professeur INP, Grenoble INP

préparée au sein du **Laboratoire G-SCOP - Sciences pour la Conception, l'Optimisation et la Production de Grenoble dans l'École Doctorale IMEP 2 - Ingénierie - Matériaux, Mécanique, Environnement, Energétique, Procédés, Production.**

Méthode simplifiée d'évaluation de la performance énergétique utilisable en conception et alimentée par des données issues de politiques publiques de produit: application aux systèmes de chauffage de bâtiments

A simplified energy performance assessment method supporting system design and fed by EU product policy data: application to heating systems in buildings

Thèse soutenue publiquement le **7 février 2018**,
devant le jury composé de :

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Dedicado a mis hijos Carlota y Mateo,
que han llegado a este mundo al mismo tiempo que esta tesis.

La finalización de esta tesis supone para mí la culminación de una etapa muy importante de mi vida. Han sido unos años muy felices aunque no siempre fáciles y bastante movidos con tanto viaje entre Italia, España y Francia. Llegados a este punto, me gustaría agradecer a todas aquellas personas que me han ayudado durante este tiempo ya sea a nivel profesional o personal.

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RÉSUMÉ

La performance environnementale des produits influence largement la performance des systèmes. De plus, les systèmes présentent encore un potentiel d'économie d'énergie inexploité pour la performance environnementale globale, comparé aux produits individuels qui les composent.

L'objectif de ce travail est de proposer une approche pour l'évaluation de performance énergétique de systèmes, en tenant compte d'information / de données livrées par les politiques européennes de produits (Directives Eco-conception et Étiquetage énergétique, Verdissement des marchés publics, Ecolabel Européen). L'hypothèse considérée ici est que les politiques environnementales des produits, qui ont été très utiles pour faciliter un système de notation homogène sur le marché européen des produits, peuvent également être avantageusement utilisées dans une démarche visant pour évaluer la performance énergétique des systèmes.

Ce travail de recherche propose une méthode simplifiée pour soutenir la conception de systèmes de chauffage performants en utilisant les données des politiques environnent ales de produits de l'Union Européenne, disponibles en phase de conception. Tout d'abord, une modélisation du système avec une approche "top-down" est utilisée pour prendre en compte les aspects système (conditions géographiques, caractéristiques du bâtiment, etc.). Deuxièmement, la performance énergétique du système est calculée à partir d'une approche "bottom-up", à partir de la performance des produits et des sous-systèmes composant le système. La méthode comporte 5 étapes divisées en deux phases principales: diagnostic du système initial et amélioration. La méthode est supportée par un outil de calcul original qui détermine les paramètres énergétiques (demande d'énergie, consommation d'énergie et rendement énergétique) au niveau du système en utilisant les données de performance telles que documentées par les politiques produits de l'Union Européenne. La méthode permet d'évaluer la performance d'un système de chauffage en définissant les systèmes les plus mauvais et les meilleurs possibles. La méthode est flexible et permet d'évaluer différentes configurations de produits et peut donc soutenir les activités de conception des systèmes de chauffage de bâtiment.

La méthode est testée sur une étude de cas, la re-conception conception d'un système de chauffage existant d'une habitation dans le nord de l'Italie, incluant un système d'eau chaude sanitaire solaire et un système de chauffage des locaux. L'étude de cas démontre le potentiel d'amélioration du système de chauffage basé sur les résultats produits par la méthode, en aidant à sélectionner les produits actuellement disponibles sur le marché. En outre, sur la base de l'évaluation, plusieurs variantes de re-conception peuvent être proposées combinant différentes performances des produits qui composent les systèmes de chauffage. La thèse analyse également l'évolution des différentes approches adoptées par les politiques de produits de l'Union Européenne (approche produit, approche produit étendu et approche système). En particulier, le concept de "package" (ou produits combinés)

défini dans les réglementations d'étiquetage énergétique des systèmes de chauffage est étudié en détail. L'étiquette du "package" du règlement 811/2013 est mise en œuvre dans la même étude de cas, de sorte que les résultats puissent être comparés à ceux des sections précédentes. Il est démontré que le concept de "package" peut également soutenir les décisions prises dans la phase de conception du système de chauffage, en particulier dans la sélection des composants appropriés en fonction de l'estimation de la performance du système. En outre, le chapitre 6, composé essentiellement d'un article publié dans un journal scientifique, analyse le lien entre les politiques publiques européennes relatives aux produits du bâtiment et celles liées à la performance énergétique des bâtiments: il est conclu qu'elles pourraient être mieux alignées.

ABSTRACT

Environmental performance of products largely influences performance of systems. Moreover, systems have still an untapped energy-saving potential concerning environmental performances at system level rather than at the level of the individual products of which they are composed.

The objective of this work is to propose an approach to deal with energy performance assessments at system level considering information/data from European product policies (Ecodesign, Energy Labels, Green Public Procurement and EU Ecolabel). The hypothesis here is that environmental product policies, that have been very useful in facilitating a homogeneous rating scheme in the EU market for individual products, can also be advantageously used in a method to assess the energy performance of systems.

This research work proposes a simplified method for supporting the design of good performing heating systems using data from EU product policies, which is available at the design stage. Firstly, a system modelling with a top-down approach is used so that system aspects (geographical conditions, building characteristics, etc.) are regarded. Secondly, the system energy performance is calculated from a bottom-up approach so that, from the performance of the products and sub-systems composing the system. The method has 5 steps divided in two main phases: diagnostic of the initial system and improvement. The method is supported by an original calculation tool which determines the energy parameters (energy demand, energy losses, energy consumption and low-emission energy efficiency) at system level using performance figures from EU product policies. It helps assessing how good a heating system is by setting the worst, benchmark and best possible systems. The method is flexible, and allows different product configurations to be assessed and can hence support the design activities of heating systems.

The method is tested on a real case study, the re-design of two existing heating systems of a dwelling in north Italy: a solar hot water system and a space heating system. The case study demonstrates the potential of improvement of the heating systems based on the results produced by the method, and helps selecting products currently available in the market. In addition, based on the initial assessment, several improved design alternatives can be proposed combining different performance levels of the products which compose the heating systems.

The dissertation also analyses the evolution of the different approaches of EU product policies (product, extended product and system approaches). In particular, the package concept set in the EU Energy Labelling regulations of heating systems is studied in detail. The package label of Regulation 811/2013 is implemented on the same prior case study so that results can be compared with the ones from applying the method proposed. It is shown that the package concept can also support decisions made in the building design phase especially in the choice of appropriate components based on estimation of system performances. In addition, it is also

analysed the link of building-related product policies with the Energy Performance of Buildings Directive, and it is concluded that they should be somehow better aligned.

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1. INTRODUCTION

1.1 Socio-economic and environmental impacts of energy in the building sector

The population growth and economic development causes an unavoidable increase in the use of energy. The European Union (EU) consumes 11.6% of the world's energy consumption. In 2015, greenhouse gases (GHGs) emissions in the EU-28 were of 4,451.8 million of tonnes of CO_2 equivalents and 8.88% was due to residential uses (Eurostat, 2017a).

The production and use of energy has great impacts on the society and the environment. It produces environmental impacts to air, water and land such as depletion of scarce resources, air and water pollution or climate change. These environmental impacts can be turned into illnesses and damages to ecosystems. Besides the costs on public health and restoration of ecosystems, energy also has an important economic burden due to the dependency on the supply and prices of fossil fuels. The EU-28 imports half of the energy it consumes and fossil fuels (petroleum and products, gas and solid fuels) represent 72% of the total energy consumption (Eurostat, 2017b). The EU has launched several initiatives for increasing the energy efficiency and reducing the energy demand with the aim of mitigating the coupling of economic growth with energy consumption. Some of these instruments are the promotion of co-generation and renewable energy sources, the energy performance of buildings and the energy labelling for domestic appliances.

The household sector accounts for 25.4% of the total energy consumption in the EU (Eurostat 2017b). The greatest energy saving potential lies in buildings (EC, 2011a). In 2012, half of the EU's energy consumption (546 Mtoe) facilitated heating and cooling, and much of this was wasted through insufficient insulation or inefficient equipment in buildings, among others (EC, 2016a). Indeed, Heating Ventilation and Air Conditioning (HVAC) systems account for 50% of the total energy consumption of buildings (Pérez-Lombard et al., 2008).

Greater energy efficiency in new and existing buildings is crucial in order to reach the goal of the European Commission's Energy Roadmap for reducing the GHGs emissions by 80-95% by 2050 compared to 1990 (EC, 2011b).The implementation of the Energy Performance of Buildings Directive (EPBD) (EC, 2010a) promotes energy efficiency by reducing the amount of energy consumed to maintain the indoor environment through heating, cooling, lighting, operating appliances and the use of renewable energy in buildings. EPBD requires Member States to set system requirements with respect of overall energy performance, proper installation, appropriate dimensioning, adjustment and control for new, replacement and upgrading technical building systems. Furthermore, the Energy Efficiency Directive (EC, 2012a) requires that 3% of the total floor area of heated and/or cooled zones of public bodies' buildings be renovated each year to meet at least requirements set in the EPBD.

The Ecodesign and Energy Labelling Directives (EC, 2009a; EC, 2010b) promote the production and consumption of more energy-efficient products. Typical Energy-using Products (EuP) used in buildings (e.g. boilers) have already been regulated for many years. The review of the Ecodesign Directive in 2009 extended its scope to include Energy-related Products (ErP), addressing other relevant building products (e.g. windows, taps and showers, insulation components). In addition, although these policies have been initially focused on products, some products groups have recently adopt a more system approach including additional components which influence the overall system performance (e.g. lighting and heating systems).

However, although policies already co-exist at the macro- (i.e. buildings, through the EPBD) and micro- (i.e. building components, through the Ecodesign and Energy Labelling Directives) levels, there is still a technological gap between building designers and regulators that needs to be filled in order to ensure the achievement of overall energy efficiency objectives (Allouhi et al., 2015).

1.2 Importance of HVAC systems design

The word system comes from Greek and means a whole compounded of arranged parts. Indeed, ancient Greek thinkers discovered the fundamentals of systems. Aristotle's famous statement "the whole is more than the sum of its parts" could be taken as the first definition of system. He studied extensively living organisms and postulated that the form and the matter could only be separated by means of abstraction. Later, the mechanical philosophy emerged bringing contradictory terms, such as reductionism and rationalism as an opposition to the holism and abstraction from Aristotle. Indeed, Galilei, Descartes, Newton or Copernicus enabled a scientific revolution which focused on decomposing matter in smaller and smaller parts (Maurer, 2017). Taking into account both approaches, "a real system is arranged in compliance with the physical elements composing the whole whereas an abstract system is arranged according to its function, with the properties characterizing the whole" (Ziebik and Hoinka, 2013). Nowadays, both the holistic-abstract and reductionist-rational approaches prevail for the analysis of systems.

Today's complex systems are composed of many components that are very heterogeneous and interact among them and within the outside environment. Some production systems (Ghadimi et al., 2015; Trevisan and Brissaud, 2016) and buildings are examples of complex systems characterised additionally by their specific interaction with their users (Cor et al., 2014) and inhabitants. The sustainability of these systems is a challenge and in particular, the energy consumption. Their performance mainly depends on decisions made at the design step.

There are huge methodological challenges regarding the definition of systems, the scope and boundaries of a system, the modelling of components that make up a system and its interactions, and the measurement of these interactions inside the system. The system definition can include greater or smaller system boundaries.

Building systems may include many components and sub-systems in charge of providing several services to users. These services can be shelter, food, HVAC systems, connectivity to internet and artificial light. This dissertation focuses on HVAC systems in buildings.

Nowadays, there are many environmental assessment methods for the design of products and systems. Ideally, environmental assessments should be done with a life-cycle perspective in order to be able to act on the life cycle phase with higher impacts. To consider all life cycle phases in environmental assessments avoids the transfer of the impacts of one life phase to another. Most of the methods are simple and qualitative (e.g. materials, energy and toxicity matrix, multicriteria analysis, etc.) while others are more complex and quantitative (e.g. Life Cycle Analysis). Ecodesign of products and systems should focus on most significant environmental aspects and life cycle phases. On the one hand, environmental performances of products largely influence performances of systems. On the other hand, systems have a great energy-saving potential at system level rather than at the level of the individual products of which they are composed.

Buildings impact the environment through different means along their life cycle (energy use, emissions to air, depletion of raw materials, water use, waste water or demolition waste, etc.) However, the use phase of buildings is by far the most important life cycle phase for existing and new buildings and this is dominated by the energy demand for heating (Nemry et al., 2010). The fact of using non-renewable energy sources generates emissions to the atmosphere as a consequence of the burning of fossil fuels. In addition, ErP installed in the building usually have higher impacts in the use phase, being the energy consumption also the main responsible. Then, reducing the energy consumption of buildings and ErP is contributing to improve the overall environmental performance.

Design of HVAC systems is often carried out according to energy (heating/cooling) demands and optimisation is rarely applied (Randaxhe et al., 2015). The choice of products to be installed in HVAC systems is usually made with regard to load calculations (Harish and Kumar, 2016). Optimisation methods have started being used recently in building design (Machairas et al., 2014).

Four European environmental product policies, Ecodesign and Energy Labelling Directives, EU Green Public Procurement (GPP) and EU Ecolabel have the common goal of making the EU market more sustainable (EC, 2008a). Indeed, they have been very successful in improving the energy efficiency of building products, especially those involved in HVAC systems such as water or space heaters (EC, 2016a). However, even greater saving potentials could be achieved when the focus is done at the system level rather than at regulating products alone. Policy makers have already recognised the limitations of considering isolated products instead of products' systems, and have proposed to move these product policies to a more system approach including additional components which greatly influence the overall performance.

In products' systems, the energy savings potential of the system approach is undervalued at market level, since usually these systems are sold by unit of product. Nowadays, the competence of ErP according to environmental product policies are based on energy efficiency figures which make consumers to choose the product which in theory, consumes less energy. But once the device has been installed, the real energy consumption can greatly vary, depending on the interactions the device has with other components of the system and with the building. Thus, to consider a system approach at the design step of products' systems is crucial for improving the overall environmental performance.

In conclusion, on the one hand, the system approach is crucial at the stage of products' systems in order to consider the system optimisation; on the other hand, the product innovation is also very relevant to reduce the energy consumption at system level. Both approaches have different target (system or products) but the same common goal: to reduce the overall energy consumption. However, in practice they are not really aligned. There is a need of bringing together these two approaches in the same direction.

1.3 Formalization of the research question

Building engineers are responsible for the proper and efficient design of HVAC systems. They should provide the technical specifications for the procurement process of the products, part of the system, to be installed.

In the market, a wide range of product performance levels, from bad to very good, can be found. The choice of the product to be installed would depend on the market availability, the price and the technical characteristics such as the nominal load or the installation requirements, among others. However, the level of performance is rarely regarded because it is difficult to make fair comparison of products. European product policy data provides a reliable rating scheme with which to make product choices based on their energy performance.

Then, a HVAC system could be composed of several products with different performance levels. In addition, each product has a different weight in the system performance. Usually, the critical products are those which directly consume the energy (energy generators) or those with high energy losses. Furthermore, the energy demand of the dwelling greatly influences the final energy consumption.

Otherwise, each dwelling and each HVAC system behaves differently according to its specific features. This makes a challenging task to know whether an HVAC system is performing well or not since there could be many acceptable solutions.

It is the system designer duty to choose a suitable combination of products performance levels which will make up a good system performance. This requires the task to predict the system performance according to different products performance levels.

General research question

How would be an appropriate energy performance assessment method to support the design of an HVAC system composed of products that have different energy performance levels?

Example: a sanitary hot water system

The sanitary hot water system is composed of an electric water heater, a distribution system, four taps and two showers. The taps and showers have high performance (awarded by an EU Ecolabel according to EC, 2013a) and the boiler has an average performance (with an energy class B according to EC, 2013b).

- Which would be the environmental performance of the system of these characteristics? Would be this a good system?
- Which component is influencing more the overall system performance, the boiler, the distribution or the taps and showers?
- If the boiler has a high performance (an energy class A) and the taps and showers an average performance (i.e. no EU Ecolabel) the system performance would be better or worse than the initial one?
- How could I most easily improve the initial system?
- Could I outweigh a bad performance of the boiler (i.e. energy class C) with a good distribution system (little losses) and good taps and showers?

This PhD presents a method useful at the design step for assessing the energy performance of heating systems based on products performances taken from European environmental product policy data.

1.4 Dissertation structure

Section 1 introduces the topic of the energy issue in the societal framework. Specific figures on energy use and environmental impact are given for the EU. Household energy use is highlighted, especially the contribution of HVAC systems in buildings. The importance to design efficient HVAC systems is also addressed. HVAC systems are part of the bigger system ‘buildings’ but are composed of many ErP. Finally, the section concludes with the research question.

Section 2 explores the State of the Art (SoA) of the main topics which could influence the development of the method. It first addresses the scientific literature review on ecodesign methods, engineering systems analysis and energy performance of HVAC systems with a detailed focus on environmental assessments on HVAC systems. Secondly, current EU product policies on HVAC systems are examined and in particular, the environmental assessment methods applied.

Section 3 presents how the PhD topic was conceived and the research methodology. In addition, this section discusses the SoA from the previous section in order to identify method requirements.

Section 4 proposes a design method and a calculation tool to be used within the method. The method has 5 steps divided in two phases: diagnostic of the initial system and improvement. The calculation tool determines the energy parameters (energy demand, energy losses, energy consumption and low-emission energy efficiency) at system level using performance figures from EU product policies. The calculation tool uses information from the method and gives feedback of results to the method.

Section 5 implements each step of the method in a real case study, a re-design of the heating systems of a dwelling in north Italy: a solar hot water system and a space heating system. The calculation tool shows how EU product policy data is used to do the system energy performance assessment. An additional economic analysis is carried out on the improved design alternatives. Finally, an extended analysis of the case study serves to check the validity of the method under changing conditions.

Section 6 analyses the recent evolution of the system approach of EU product policies, in particular the package label applied to heating systems. These topics are addressed through a scientific paper recently published in the journal Energies.

The dissertation finalises with an overall discussion of the method, main conclusions and added value, limitations and perspective (Section 7).

2. STATE OF THE ART

2.1 Environmental assessment methods applied to ecodesign

Mass production of industrial products causes great environmental impacts, not only during its manufacturing but also when these products are distributed, used and further disposed. The importance of considering life cycle thinking in the design of products reduces the potential shifting of impacts from one life cycle phase to another one.

In this regard, some ISO standards provide guidelines to assess and report the environmental performance of products. These include Environmental Labels and Declarations (ISO 14020, 14021, 14024 and 14025), Life Cycle Assessment (ISO 14040 and 14044) and Design for environment (ISO/TR 14062). Their common goal is to provide guidance on the improving of products from an environmental point of view.

Most of the environmental impacts along the life cycle of products could be avoided if environmental aspects are regarded at the early stage of design. Ecodesign or Design for the Environment minimises significant environmental impacts of all life cycle phases of a product's life and considers stakeholders requirements in the design and development of a product (ISO/TR 14062:2002).

Several environmental assessment methods can be applied to design. Life cycle assessment (LCA) quantifies environmental impacts in all the life cycle stages of a product, from the raw material extraction, material processing, manufacturing of the product, its use, and end-of-life (ISO 14040:2006). However, the time and effort needed to perform a complete LCA might not be practical for design (Millet et. al, 2007). Streamlined LCA could be more appropriate regardless the loss of accuracy on the results (Verghese at al., 2010).

Then, it is acceptable that design for the environment focuses only in those life cycles and/or environmental aspects which have higher impacts. Furthermore, the consideration of the environmental dimension in addition to the conventional design requirements with a life cycle approach could be enough to call it ecodesign. Indeed, the assessment criteria in the design of products should be the result of a multidimensional analysis. Product design should be a compromise solution between various requirements identified at different life cycle stages. These requirements include aspects such as, functionality, cost efficiency, durability, safety, resource efficiency, etc.

Under these premises, other simpler methods could be applied to ecodesign such as the Materials Energy and Toxicity (MET) matrix (Knight and Jenkins, 2009), checklists (Moultrie et al., 2016) , multicriteria analysis (Ramanujan et al., 2014), the Strengths, Weaknesses, Opportunities and Threats (SWOT) matrix (Pesonen and Horn, 2012), eco-roadmap (Donnelly et al., 2006), hierarchy of focussing (Hauschild et al., 2004) and life cycle costing (LCC) (Iraldo et al., 2017) among others.

Many authors have used LCA on building design (Azzouz et al., 2017; Russell-Smith, 2015; Basbagill et al., 2013). Checklists are used for building sustainability performance assessment such as in BREAM or LEED certifications. Multicriteria and SWOT analysis have been also applied to assess environmental performance of buildings (Kabak et al., 2014; Stevanovic et al., 2017). LCC has been used often for building design (Goussous and Al-Refaie, 2014; Liu et al., 2015; Aparicio-Ruiz et al., 2014).

In conclusion, several environmental methods exist with a life cycle perspective but the simpler ones are more suitable for the early stages of design. Furthermore, such methods have been already used to assess environmental performance of buildings. A detailed review on environmental assessments on HVAC systems is given forward in section 2.4.

2.2 Engineering systems: the case of HVAC systems in buildings

As introduced in section 1.2, system analysis could be done in two directions. The first one is focusing in the system (Aristotle's view), its behaviour as a whole and how its parts contribute to the overall behaviour and thus, a top-down approach. The second one is focusing in decomposing the system into smaller parts (Galilei, Descartes, etc. view) and studying their individual behaviours in order to predict how the system behaves and thus, bottom-up approach. Nowadays, both approaches are useful for system analysis. However, the top-down approach is more complex and less implemented.

From an engineering point of view, the International Council of Systems Engineering, defines a system as a group of elements that work together to enable results that would not be possible by the elements alone (INCOSE, 2017). Complex systems are characterised by many connected elements which interact among themselves and with the whole. Examples of complex systems are some manufacturing processes (e.g. automotive or aeronautical), product service-systems (e.g. data centres or product leasing) or energy grids. In this regard, buildings could be considered as complex energy systems since they are composed of many materials and components which interact among them and with the outside environment. In addition, user interactions with the building also influence the energy performance of the whole building (Peuportier et al., 2013).

The performance of complex systems is dynamic and changes according to conditions of use, maintenance, component upgrading, etc. (Tchertchian et al., 2016). During the conceptual design of complex engineering systems not all the information is available and the collection, understanding and analysis of data could be a challenging task (Amaechi and Counsell, 2012). The decisions made in the building design phase (Annunziata et al., 2016) and in particular on the components chosen to compose the system are crucial to avoid major environmental impacts.

HVAC systems are part of the bigger system "building" and at the same time, each of these systems is composed of several components and/or sub-systems which aim at

delivering the required service (heat, ventilation or air conditioning) to users. However, each component/sub-system has its own particular sub-function and they are physically connected and/or interrelated among them. For instance, the European Standard CEN 15316-1 (CEN, 2006) on heating systems in buildings considers the following components' functions: the energy generation, the storage, the distribution, the delivery of the service and the controls.

To sum up, HVAC systems ecodesign should consider the outside environment and the building in which they are installed as well as the products which they are composed of.

2.3 Energy performance of HVAC systems in building design

From the whole life cycle of ErP and EuP, the use phase is by far the phase with highest environmental impacts mainly due to the energy consumption (see section 1.2). Therefore, the ecodesign of these products should focus in improving the energy efficiency and thus, in reducing the energy consumption in the use phase. In a building, the energy consumption of HVAC systems depends on its energy efficiency as a system and on the energy required (or demand) of the dwelling in which these are installed.

The general formula of the energy efficiency (η) of a system is defined as the ratio between the energy output and the energy input.

Equation 1:

$$\eta = E_{OUTPUT}/E_{INTPUT}$$

At component level, the energy efficiency of equipment is the percentage of total energy input that is consumed in useful energy. At the building level, according to the EPBD Directive (EC, 2010a), the 'energy performance of a building' means the calculated or measured amount of energy needed to meet the energy demand associated with a typical use of the building, which includes, inter alia, energy used for heating, cooling, ventilation, hot water and lighting.

According to EPBD, a building that has a very high energy performance is called a 'nearly zero-energy building' and is that one in which very low amount of energy is required and this should be covered mainly by energy from renewable sources. In other words, the goal of these buildings is to minimise the (non-renewable) **energy consumption**. In summary, a low energy demand and the use of renewable energy sources is crucial to reduce the energy consumption. A low **energy demand** could be achieved for instance with good wall and windows isolation, with high equipment efficiencies or with low **energy losses** of components. The use of renewable energies sources reduces the need of non-renewables.

Thus, following the same reasoning, aN HVAC system that has a very high performance is that one which requires low energy and in which this, should be covered in a great extent by renewable energy. This approach has been used not only by the EPBD but also in other building-related policies oriented towards low-

emission designs such as Regulation 811/2013 (EC, 2013e). In fact, this has been an effective way in which such policies have rewarded renewable energy sources as well as energy-saving components.

One way to give credits to installations which use renewable sources is not including the renewable energy in the efficiency formula as part of the energy input (Equation 1). Then, the energy efficiency is the ratio between the energy demand and the energy consumption (Pérez-Lombard et al., 2011). This efficiency is also called low-emission energy performance (Fesanghary et al., 2012) because it aims at minimising the non-renewable energy and thus, to reduce the effect of emissions to atmosphere such as CO_2 or equivalents originated mainly from the burning of fossil fuels. Then, efficiencies higher than 100% are accepted under this definition of efficiency.

Simulation tools have been used in the past forty years to integrate multiple aspects of building and HVAC system design based on technical and usage performance or on energy consumption, among others (Ellis and Mathews, 2002). Indeed, energy assessment tools of the building behaviour have been a key factor of success of building energy regulations in effectively controlling the energy consumption (Allouhi et al., 2015). However, simulation tools are rarely used during the design phase of the building (Schlueter and Thesseling, 2009). In Europe, the energy certification of buildings according to EPBD is calculated before the users start to use the dwelling, so that all the HVAC devices are already installed.

Simulation software needs detailed and numerous data. However, during the design process, the collection of data is time consuming. Thus, although building simulation tools can precisely model HVAC systems, sometimes fail when they cannot be fed with enough and adequate data in the early design stages, and deliver useful results quite late in the design process. These tools require product parameters that often are not supplied by products' manufacturers. They are time consuming and some are expensive. In addition, despite the increased number of improvements in simulation tools, there can still be up to 40% difference between predicted and real energy consumption in buildings (Trčka and Hensen, 2010). Thus, some loss of accuracy might be acceptable if the design process could be sped up. When data is not all available, some calculations should be estimated with more or more or less accuracy depending on the time and effort the designer is willing to invest. Simplified tools such as conceptual system design or the use of simple equations or rules of thumb require less input data, lower user expertise and yield more easily interpreted results.

Trčka and Hensen (2010) stated that a combination of HVAC simulation tools with conceptual design could be useful in system modelling since the advantages of the former match well with the flexibility of the latter. The combination of complex and simple tools has been often used in the environmental impact assessments of HVAC solutions (e.g. Zambrana-Vasquez, 2015; Yang et al., 2008). BREEAM and LEEDS certification schemes combine computer tools to determine the energy performance

of the building together with checklists and/or scales to give credits to the better performing buildings.

BREEAM building certification provides two options to recognise buildings that minimise the operational energy consumption through a good design. The first assessment option is to use approved building energy calculation software and takes into account the building's operational energy demand, the buildings' primary energy consumption and the total resulting CO_2 emissions. Modelling should be carried out by a suitable qualified energy modelling engineer. A benchmark scale is provided so that to award with more or less BREEAM credits. When the first option is not available, a second option determines the energy performance of the building using a checklist, which set the number of credits available for this issue (BREEAM, 2017a). This checklist includes lighting, water heat generator efficiency, low and zero carbon technologies, building fabric, space heat generator efficiency and cooling and ventilation (BREEAM, 2017b).

Likewise, LEED building certification for homes provides also two ways for optimising the energy performance. The first one is using ENERGY STAR and FEMP (Federal Energy Management Program) which designate energy efficient products and the use of a building energy simulation computer tool. The second one consists in following eight steps: 1. determine the climate zone, 2. identify energy use target for building, 3. research and designate energy efficient products, 4. engage an energy modeller to perform energy analysis, 5. develop preliminary energy model, 6. model potential HVAC system types, 7. develop energy model for proposed design, and 8. establish energy baseline (USGBC, 2017).

There are many building performance tools which model HVAC systems such as tools for pipe/duct sizing (AFT Fathom, DOLPHIN, Duct Calculator, etc.) for equipment sizing and selection (Carrier HAP, Trane TRACE 700, EnergyPLus, etc.), for control analysis (EnergyPlus, TRNSYS, MATLAB, etc.), for energy performance analysis (Carrier HAP, Trane TRACE 700, EnergyPLus, etc.) or for system optimisation (GenOpt). As shown in the examples, usually, the same tool does several types of analysis. Tools for energy performance analysis and system optimisation are used to calculated different sub-system performances, to analyse system operation strategy and to compare alternatives (Trcka and Hensen, 2010). They model each sub-system of the dwelling for predicting firstly the energy demand (from the geographical context, building envelope, solar irradiation, user behaviour, etc.) and secondly, the energy consumption of HVAC systems through energy balances according to the installed equipment (heat/cool/light generators, fluid distribution systems, storage equipment, heat/cool/ventilation emitters, etc.).

To conclude, a good performing building is that one that requires low amount of energy and this is provided by renewable sources. A low energy demand could be achieved with a proper building and installations isolation (avoiding losses) or through high equipment efficiencies. In addition, simulation tools combined with simple methods are useful in design and are already used (e.g. BREEAM, LEED).

2.4 Environmental assessments of HVAC systems in the scientific literature

In this section, the results of the analysis of 17 scientific papers with regard environmental assessments in HVAC systems are presented. The environmental assessments of these papers are all carried out from 'systems to products' (top-down approach) and they cover different building services (Table 1).

Table 1. Services delivered by HVAC systems in the scientific literature (own analysis)

Scientific paper	Sanitary hot water	Space heating	Space cooling	Ventilation
Yang et al., 2008		x		x
Shah et al., 2008		x	x	
Beccalli et al., 2012		x	x	
Koroneos et al., 2012	x	x	x	
Debacker et al., 2013	x	x		x
Prek, 2004		x		
Qu et al., 2010		x	x	
Hang et al., 2012	x			
Abusoglu and Sedeeq, 2013		x		
Zambrana-Vasquez et al., 2015	x			
Blom et al., 2010		x		x
Nyman and Smonson, 2005				x
Ucar et al., 2006		x		
Morrison et al., 2004	x	x		
Chyng et al., 2003	x	x		
Heikkila, 2006			x	
Heikkila, 2004			x	

From Table 1 it can be concluded that only few of the considered HVAC systems deliver only one service and most of them include a heating system.

The top-down analysis has delivered a number of components of each of the HVAC systems analysed in the literature review. The HVAC system is decomposed into their integrated parts (products or components and sub-systems). Then, I decided to classify components according to the function they deliver inside the HVAC system (CEN, 2006); generation of the service, storage, distribution or control. Equivalent products are those fulfilling the same function. Analysing the function of components one by one of all the papers, additional sub-functions were identified (Table 2). Hence, it was possible a more detailed classification of components, according to their sub-function in the system (Table 2 and Table 3).

Table 2. Functions and sub-functions identified in HVAC components in the scientific literature review (own analysis)

FUNCTION	SUB-FUNCTION
PRODUCTION OF THE SERVICE	Harvest of energy
	Storage of energy carrier
	Conversion/transfer energy
	Storage of the medium or the service
	Evacuation/exchange of gases
	Protection
DISTRIBUTION	Distribution of the medium or the service
DELIVERY	Delivery of the end-use service
CONTROLS	System controls

Table 3 shows the detail of the analysis of only 6 relevant references (from those 17). HVAC systems from the analysed papers are very heterogeneous with regard of the type of components they include. Papers considering passive services i.e. those which do not use energy (e.g. natural ventilation) were not included in the analysis. Then, all the systems analysed in the journal papers include a component which produces the service, either by generating and/or by harvesting the energy. Distribution components are mostly considered in the papers (when they are present in the system). Delivery components and controls were mentioned but not included in the journal papers analysed; however, other papers exist only focused on these components (e.g. Rhee and Kim, 2015).

The task of classifying every component of each systems found in the journal papers allowed the identification of the sub-functions proposed in Table 2. Consequently, any component of a HVAC system (at least of those 17 journal papers analysed) could be classified in one of the sub-functions proposed.

Table 3. Components identified in environmental assessments of HVAC systems in the scientific literature (own analysis)

SCIENTIFIC PAPERS		COMPONENTS' FUNCTIONS								
		PRODUCTION of the service						DISTRIBUTION	DELIVERY	CONTROL
Reference	COMPONENTS SUB-FUNCTIONS/ SYSTEMS INCLUDED	Harvest of energy	Storage of energy carrier	Conversion/ transfer of energy	Storage of medium or the service	Evacuation/ exchange gases	Protection	Distribution of the medium or the service	Delivery of end-use service	Controls
Yang et al., 2008	1. Two-pipe hot water heating (boiler) system with mechanical ventilation	-	-	Boiler Heat recovery ventilator	-	-	Expansion tank	Pipes and fittings (water) Circulating pump	Radiators	-
	2. Forced air heating (furnace with blower) system.	-	-	Furnace	-	-	-	Ducts (air)	Diffusers	-
Shah et al., 2008	1. Central natural gas furnace heating and conventional central air-conditioning	-	-	Furnace Air conditioner	-	Chimney	-	Duct network (cold and warm air)	Fan coil (air conditioner)	-
	2. Natural gas powered hydronic heating and conventional central air-conditioning	-	-	Boiler Condenser unit	-	-	-	Pipe network (water) Ducts (air)	Radiators Fan coil	-
	3. Electric air–air heat pump for heating as well as cooling.	-	-	Heat pump	-	-	-	Ducts	-	-
Beccalli et al., 2012	Solar heating and cooling system	Evacuated tube solar collector field		Absorption chiller Auxiliary gas boiler	Hot water storage tank	Wet cooling tower		3 pumps	2 pipe fan coil units	-

SCIENTIFIC PAPERS		COMPONENTS' FUNCTIONS								
		PRODUCTION of the service						DISTRIBUTION	DELIVERY	CONTROL
Reference	COMPONENTS SUB-FUNCTIONS/ SYSTEMS INCLUDED	Harvest of energy	Storage of energy carrier	Conversion/ transfer of energy	Storage of medium or the service	Evacuation/ exchange gases	Protection	Distribution of the medium or the service	Delivery of end-use service	Controls
Koroneos et al., 2012	1. Solar heating system	Solar collector Geothermal pipes	-	Solar heat exchanger Geothermal heat exchanger	Hot water storage tank	-	-	-	In-floor pipe system (water)	-
	2. Domestic hot water system	Solar collector Geothermal pipes	-	Solar heat exchanger Geothermal heat exchanger Electric resistance	Hot water storage tank	-	-	pipes	-	-
	3. Solar cooling system	Solar collector	-	Absorption chiller Auxiliary electric resistance	Cold water storage tank. Hot water storage tank	Cooling tower	-	-	In-floor pipe system (water)	-

SCIENTIFIC PAPERS		COMPONENTS' FUNCTIONS								
		PRODUCTION of the service						DISTRIBUTION	DELIVERY	CONTROL
Reference	COMPONENTS SUB-FUNCTIONS/ SYSTEMS INCLUDED	Harvest of energy	Storage of energy carrier	Conversion/ transfer of energy	Storage of medium or the service	Evacuation/ exchange gases	Protection	Distribution of the medium or the service	Delivery of end-use service	Controls
Debacker et al., 2013	1.Space heating services (different generators)	-	-	Gas boiler Heat pump Oil boiler Pellet furnace	-	-	-	-	Panel radiator (steel plate) Floor heating	Manual valves Clock control Room thermostat Outside temperature sensor
	2.Domestic hot water services (different systems)	-	-	Geyser (gas boiler) Electric boiler Oil boiler Heat pump Pellet furnace Solar boiler	Different capacities of hot water storage tank	-	-	-	-	-
	Ventilation	-	-	Single exhaust ventilator Supply ventilator	-	-	-	-	-	-
Qu et al., 2010	Solar thermal absorption cooling and heating system	Linear parabolic through solar	-	Double effect absorption chiller Heat recovery heat exchanger Auxiliary gas boiler	-	Cooling tower	Expansion tank Three-way valve	Pump	-	-

Table 4 summarises the type of methodologies to assess environmental performance of the HVAC systems found in the scientific literature.

Table 4. Types of environmental assessments on HVAC in the scientific literature

Scientific paper	TYPE OF PERFORMANCE ANALYSIS	TYPE OF ENVIRONMENTAL ASSESSMENT
Yang et al., 2008	Coefficient of Performance of the HVAC system. Expanded cumulative exergy consumption.	Life-cycle energy use: pre-operation + operation phases (not LCA methodology). GWP of embodied impacts.
Shah et al., 2008	-	SimaPro 5.0 software. Franklin and ETH-ESU databases. Impact 2002+ method: 14 midpoint categories.
Becalli et al., 2012	Global Energy Requirement, NRE, energy return ratio. Primary energy consumption.	SimaPro software. Ecoinvent database. Cumulative Energy demand (CED) and EPD 2008 methods.
Koroneos et al., 2012	Exergy analysis (use phase)	SimaPro and Gabi (software and databases). 8 impact categories. Only manufacturing phase.
Debacker et al., 2013	-	Ecoinvent database, among other sources. Cradle to grave.
Prek, 2004	-	Eco-indicator 95 method
Qu et al., 2010	System performance (+system optimisation). Renewable energy use	-
Hang et al., 2012	-	SimaPro 7.1 software. Ecoinvent database. CED. Cradle to grave. Carbon footprint.
Abusoglu and Sedeeq, 2013	Energy and exergy analysis	SimaPro 7.1 software. Ecoinvent database. Impact 2002+ (14 mid-point environmental aspects)
Zambrana-Vasquez et al., 2015	-	SimaPro 7.3.2 software. Ecoinvent 2.2 database. CML2 baseline 2000 V2.05 method. 10 impact categories. CED.
Blom et al., 2010	-	Ecoinvent, Idemat and EcoQuantum databases. CML 2000. 9 impacts categories.
Mikko et al., 2005	-	LCA
Ucar et al., 2006	Exergoeconomic analysis. Optimisation.	-
Morrison et al., 2004	Seasonal performance	-
Chyng et al., 2003	COP (Coefficient of Performance)	-
Heikkila, 2006	-	LCA. EPS Design System 4.0. 4 impact categories.
Heikkila, 2004	-	LCA. EPS Design System 4.0. Weighting (EPS 200 default method).

LCA is used in 12 of the 17 scientific papers analysed. Almost all the LCAs are carried out with software and/or databases. Performance analysis is also undertaken (8 of 17) in terms of energy consumption, exergy or energy performance. In addition to the use phase, some papers consider the manufacturing phase (e.g. Yang et al., 2008 or Koroneos et al., 2012). However, as expected, results of the analysis carried out in the journal papers show that most of the environmental impacts concentrate in the use phase and this is due to the energy consumption. Exergy analysis is undertaken in 4 papers in order to include the efficiency of the production of the energy sources used by the HVAC systems.

To summarise, HVAC systems analysis in the scientific literature show that they usually deliver more than one service. This fact makes system analysis even more complex. Heating systems are included in most of the papers analysed. Decomposing these systems into components or products, common functions and sub-functions are identified for all HVAC products found in the literature (17 scientific papers). LCA is often used as environmental assessment method; however, only one assessment is carried out at the design stage (Qu et al., 2010). Almost all papers (except for those in which only the manufacturing phase is assessed) conclude that energy consumption in the use phase is the most important environmental impact.

2.5 Analysis of EU product policies on HVAC systems

This section focuses on four product policies: the Ecodesign and Energy Labelling Directives (EC, 2009; EC, 2010b), Green Public Procurement (GPP) (EC, 2008b) and the EU Ecolabel (EC, 2010c). The common goal of these product policies is to make the EU market more sustainable (EC, 2008a). From a market perspective they have different objectives and they are also addressed to different actors (Table 5).

Table 5. Principles of European product policies (Calero-Pastor et al., 2014)

European Product Policies	**Market objective**	**Mandatory?**	**Targeted actor of the policy**
Ecodesign Directive	Cut out from the market the least environmental performing products	Yes	Market authorities
Labelling Directive	Push the market towards more environmentally performing products	Yes	Consumers
EU Green Public Procurement	Increase the market of good environmentally performing products	No	Public administration
EU Ecolabel	Awards the environmental excellence of products	No	Consumer and businesses

These four product policies represent all the range of performance levels available in the market, from the products with less to the ones with most energy performance. Minimum performance requirements are guaranteed through the Ecodesign Directive. The Ecodesign and Labelling Directives are compulsory for certain ErP and GPP and EU Ecolabel establish voluntary measures for some product categories. According to these product policies, manufacturers and/or importers should provide information regarding the performance of the products they put on the EU market. Then, information on components' performances covered by such EU product policies is available to designers, either in such regulations or through the technical documentation of the product provided by the manufacturer.

Product policies initially addressed individual products. However, it was soon seen the importance of considering additional products or components that were greatly influencing the overall energy efficiency. The extended approach in products' systems consists in extending the system boundaries in order to include other products influencing the performance of the product under study. The system approach considers all (or part of) the components and sub-systems needed to deliver a service and has been only applied in Ecodesign and Energy Labelling of motor and lighting systems. The "package concept" is considered in this section as a type of extended product approach. However, it could also be considered as a sub-system approach since they include a group of components (or products) but not all of them.

Nevertheless, BRE (Young et al., 2011) analysed the implementation of the system approach in product policies and identified the following risks:

- For developing robust system methodology, the length of the technical discussion by stakeholders might become too long.
- The system approach may become too difficult and this additional complexity might lead to higher costs and longer timescales.
- The system approach might not correspond to markets since industry operates at product or component level (unit of sales).

So far, product policies have dealt with the particularities of motor, lighting, heating and cooling systems. Next, current product policies on HVAC systems are analysed from products to systems (bottom-up approach) and main environmental requirements are presented.

2.5.1 EU product policies features in heating and cooling systems

These systems are usually regulated according to the service they deliver (sanitary hot water, space heating or space cooling), the energy source they use (liquid, gas or solid fuels, electricity, etc.) or their specific features (water-based or not).

The product approach is dominant in product policies of these systems, so that individual heaters or coolers are regulated separately. There are also regulations

such as Ecodesign 814/2013 that cover more than one product (Figure 1), in this case, water heaters and storage tanks, both part of the heating system but with different sub-functionalities and thus, assessed with different performance methods. Regulation 813/2013 includes equipment designed to deliver one (space heaters) or two functions (combination heaters that deliver sanitary hot water and space heating). Regulation 812/2013 sets energy labelling requirements for packages of water heaters with storage tank and solar device once they have been installed together (extended product approach). Energy labelling of solid fuel boilers (Regulation 1187/2015) include also packages of a solid fuel boiler, temperature controls and solar devices (extended product approach).

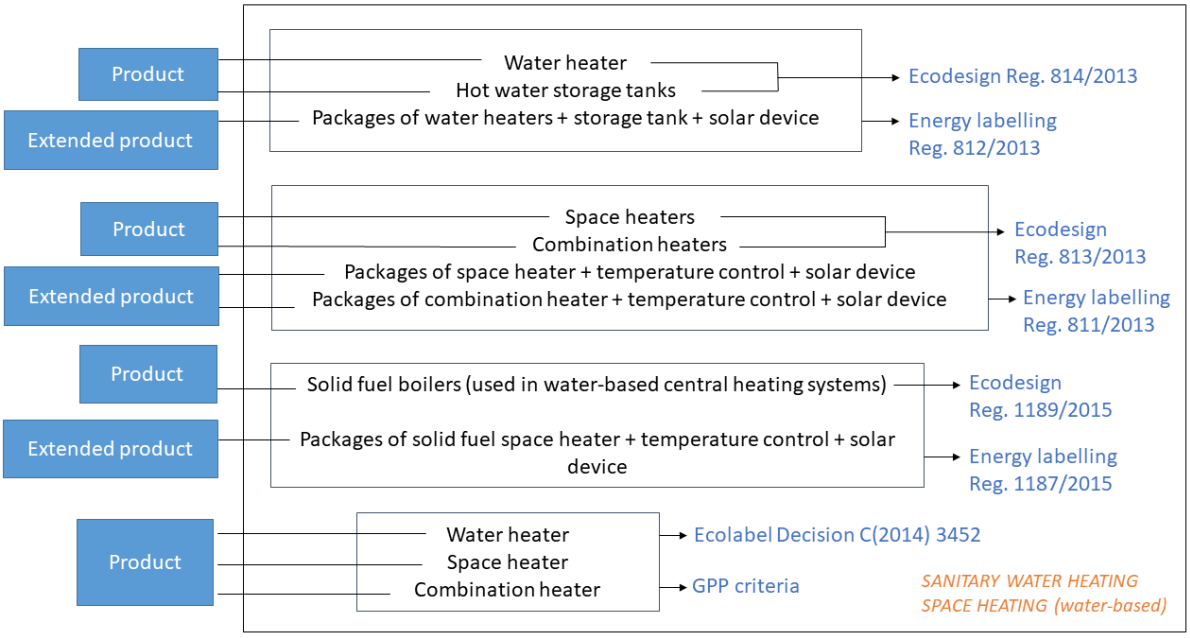


Figure 1. Overview of EU product policies on water-based heaters

Regulations 814/2013, 812/2013, 813/2013 and 811/2013 have different product scope but they use similar parameters to assess the performance of their products. The water energy efficiency is assessed in water heaters that deliver sanitary hot water according to different load profiles set under real test conditions (tapping patterns). In the case of space heaters, the main parameter assessed is the seasonal energy efficiency. In combination heaters both functions (sanitary water heating and space heating) are assessed separately. In storage tanks, Ecodesign requirements set maximum storage volumes and standing losses. Other performance parameters assessed in these regulations are sound power levels or nitrogen oxides emission (in fossil fuel water heaters). In addition to these parameters, Regulation 1189/2015 on the Ecodesign of solid fuels boilers (sanitary water heating and/or space heating and/or electricity generation), set maximum levels of organic gaseous compounds and carbon monoxides. EU Ecolabel (EC, 2014a) and GPP criteria for water-based heaters (EC, 2016b) are on high energy efficiency, low air emissions (GHG,

refrigerants, NOx, CO, OGC, PM and other hazardous substances) and low noise emissions, among others.

With regard to local space heaters (Figure 2), similar parameters to the previous ones are assessed for Ecodesign of (not water-based) solid fuel local space heaters (Regulation 1185/2015), Ecodesign of local space heaters different of solid fuels (Regulation 1188/2015) and the energy labelling for local space heaters including solid fuels and excluding electricity (Regulation 1186/2015). All these regulations follow the product approach.

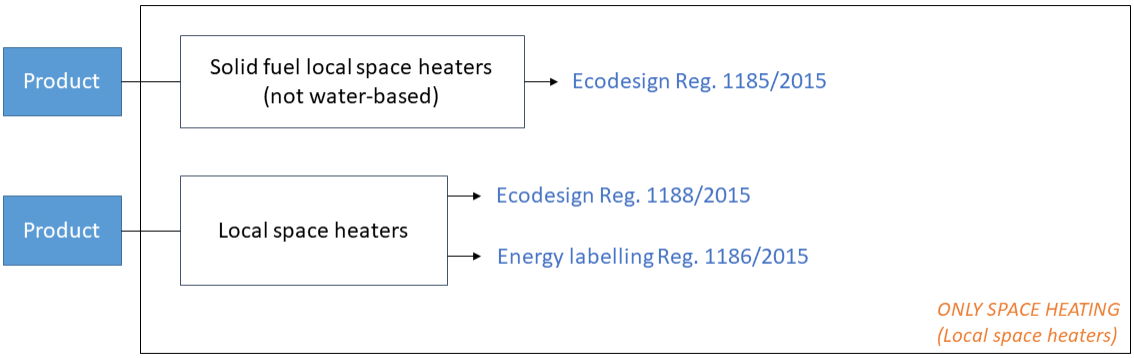


Figure 2. Overview of EU product policies on local space heaters

Equipment for space cooling function (Figure 3), may provide additional functions such as space heating, ventilation or de-humidification; however with a product approach. Ecodesign requirements for air conditioners and fans (Regulation 206/2012) are set for minimum energy efficiency, maximum electricity consumption and sound power levels. In addition, the type of refrigerant used may penalize (or not) the total energy efficiency. Energy labelling on air conditioners (Regulation 626/2011) set energy classes for different types of air conditioners according to the cooling and/or heating function and for different climate zones.

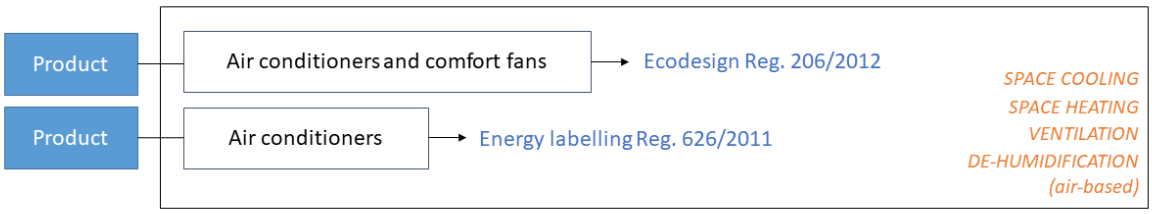


Figure 3. Overview of EU product policies on air conditioners

To sum up, the energy performance of packages (groups of products) is common practice in some heating systems with solar devices and/or storage tank and/or temperature controls, and the performance of the package is assessed through the extended product approach and under installed conditions. The system approach is not widely used in product policies. However, due to the particularity of some equipment, more than one function may be assessed in the same product.

2.5.2 Environmental assessments of HVAC systems in EU product policies

HVAC systems may deliver more than one function and this is considered in some EU product policies (Table 6). Cogeneration heating systems which have the additional secondary function of providing electricity are also included.

Table 6. Services delivered by HVAC components regulated by EU product policies (own analysis)

SERVICE DELIVERED / PRODUCT GROUP	Sanitary hot water	Space heating	Space cooling	Ventilation	Electricity
Water heaters and hot water storage tanks (*ED, GPP and EU Ecolabel) and packages of water heaters and solar device (ED and **ELD)	X				
Space and combination heaters (ED, GPP and EU Ecolabel) and packages of space heaters, temperature control and solar device and packages of combination heaters, temperature control and solar device (ED, ELD, GPP and EU Ecolabel)	X	X			X
Solid fuel boilers and packages of solid fuel space heaters and temperature control and solar device (ED, ELD, GPP and EU Ecolabel)	X	X			X
Solid fuel local space heaters (ED)		X			
Local space heaters (ED and ELD)		X			
Air conditioners (ED and ELD) and comfort fans (ED)		X	X	X	
Ventilation units (ED) and residential ventilation units (ELD)		X		X	
Glandless standalone circulators and glandless circulators integrated in products (ED)		X	X		

**ED = Ecodesign and **ELD = Energy Labelling Directive*

Table 7 shows which products are in the scope of each of these product policies (including products alone and as part of a package). Product policies allow making fair comparisons of products. Two products could be compared, only if they are equivalent products. Similar products could be considered equivalent if they deliver the same function within the system. Then, from the analysis of the types of products covered by product policies, products are classified according to the function they deliver inside the HVAC system (CEN, 2006); generation of the service, storage, distribution or control (Table 7). This is consistent with the analysis carried out in Table 3 with scientific papers.

Table 7. HVAC products/components covered by EU product policies, per function in the system (own analysis).

PRODUCT FUNCTION/ EU PRODUCT POLICY	GENERATION OF THE SERVICE	STORAGE	DISTRIBUTION	CONTROL
Ecodesign (Regulation 814/2013) and Energy Labelling (Regulation 812/2013), EU GPP of water-based heaters and EU Ecolabel Decision 3452/2014	Water heaters (sanitary hot water)	Storage tanks (independent from water heaters)	-	-
In addition, Energy Labelling (Regulation 812/2013)	Packages of water heaters and solar device (sanitary hot water)	Storage tanks (as part of the package)	-	-
Ecodesign (Regulation 813/2013) and Energy Labelling (Regulation 811/2013) EU GPP[4] and EU Ecolabel Decision 3452/2014	Space heaters (space heating)	-	-	-
	Combination heaters (sanitary hot water and space heating)	-	-	-
In addition, Energy Labelling (Regulation 811/2013), GPP[4] and EU Ecolabel	Packages of space heaters + solar device + supplementary heater (space heating)	Storage tanks (as part of the package)	-	Temperature control (as part of the package)
	Packages of combination heaters + solar device + supplementary heater (sanitary hot water and space heating)	Storage tanks (as part of the package)	-	Temperature control (as part of the package)
Ecodesign (Regulation 1189/2015) and Energy Labelling (Regulation 1187/2015) EU GPP[4] and EU Ecolabel Decision 3452/2014	Solid fuel boilers (space heating, sanitary hot water, electricity)	-	-	-
In addition, Energy Labelling (Regulation 1187/2015) EU GPP[4] and EU Ecolabel Decision 3452/2014	Packages of solid fuel boiler + solar device + supplementary heater (space heating, sanitary hot water, electricity)	Storage tanks (as part of the package)	-	Temperature control (as part of the package)
Ecodesign (Regulation 1185/2015)	Solid fuel local space heaters (space heating)	-	-	-
Ecodesign (Regulation 1188/2015) and Energy Labelling (Regulation 1186/2015)	Local space heaters (space heating)	-	-	-
Ecodesign (Regulation 206/2012) and Energy Labelling (Regulation 626/2011)	Air conditioners (space cooling, space heating and ventilation)	-	-	-
Ecodesign (Regulation 1253/2014) and Energy Labelling (Regulation 1254/2014)	Ventilation units (ventilation and space heating)	-	Ducts (part of the system)	Controls (part of the system)
Ecodesign (Regulation 641/2009)	-	-	Glandless standalone circulators	-

Table 7 shows that the majority of the products affected by product policies are heat/cool generators so that they have the function to generate a HVAC service. This makes sense since most EU regulations aim at reducing the energy consumption. However, since products with other functions within the system also have an influence on the final energy consumption, product policies consider some of them as part of a package. The only product group which is not a generator and that is regulated alone, and not as part of a package, is “storage tanks” (see section 2.5.1).

Table 8 summarises the environmental aspects included in product policies of HVAC systems. Since almost all the products are ErP, this product policies focus in the use phase, either in the energy efficiency or in the energy consumption. For each product policy and product group, a different methodology to calculate the energy efficiency is applied.

In addition to the environmental aspects mentioned in Table 8, there are information requirements which contribute to a proper use, maintenance, repair and disposal of the products. This information is not included in Table 8.

Table 8. Summary of environmental aspects included in EU product policies of HVAC components (own analysis)

ENVIRONMENTAL ASPECT/ PRODUCT POLICIES	Energy efficiency	Energy consumption (or energy losses)	Air emissions	Technical requirements influencing environmental aspects	Presence of hazardous substances	Sound power level
Regulation 814/2013 on Ecodesign of water heaters and storage tanks.	Water heating energy efficiency in water heaters	Auxiliary electricity consumption is included in the water heating energy efficiency in water heaters. Maximum standing losses in storage tanks.	Nitrogen oxides in water heaters using liquid and gaseous fossil fuels.	Minimum volume of water mixed at 40C in water heaters. Maximum storage volume in storage tanks.	No	In water heaters
Regulation 812/2013 on Energy Labelling of water heaters, hot water storage tanks and packages of water heater and solar device	Water heating energy efficiency in water heaters and in packages of water heaters, storage tank and solar device. Standing loss in storage tanks.	Auxiliary electricity consumption is included in the water heating energy efficiency in water heaters. Annual electricity consumption in water heaters. Standing loss in storage tanks.	No	No	No	In water heaters
Regulation 813/2013 with regard to Ecodesign requirements for space heaters and combination heaters	Seasonal space energy efficiency in space heaters. Seasonal space energy efficiency and water heating energy efficiency in combination heaters.	Auxiliary electricity consumption included in the seasonal space heating energy efficiency.	Nitrogen oxides (NO_x) in space heaters using liquid and gaseous fossil fuels.	No	No	In heat pump space heaters and heat pump combination heaters

ENVIRONMENTAL ASPECT/ PRODUCT POLICIES	Energy efficiency	Energy consumption (or energy losses)	Air emissions	Technical requirements influencing environmental aspects	Presence of hazardous substances	Sound power level
Regulation 811/2013 Energy Labelling of space heaters, combination heaters, packages of space heater, temperature control and solar device and packages of combination heater, temperature control and solar device	Seasonal space energy efficiency in space heaters and packages of space heater, temperature control and solar device Seasonal space energy efficiency and water heating energy efficiency class in combination heaters and packages of space heater, temperature control and solar device Standing loss in solar hot water storage tanks, if part of a solar device.	Auxiliary electricity consumption included in the seasonal space heating energy efficiency.	No	No	No	In all the products in the scope of the regulation
GPP and EU Ecolabel for water-based heaters	Water heating energy efficiency. Seasonal space heating energy efficiency		Greenhouse gases, NO_x, organic monoxide (CO), organic gaseous compounds (OGC), and particulate matter (PM) emissions in heaters using liquid and gaseous fossil fuels.	Marking of plastic parts	Refrigerant and secondary refrigerant in heat pumps. Hazardous substances and mixtures	In fuel-driven, electrically-driven heat pump heaters and cogeneration space heaters
Regulation 1189/2015 on Ecodesign of solid fuel boilers	Seasonal space heating efficiency	Auxiliary energy consumption included in the seasonal space heating efficiency	Seasonal space heating emissions of PM. OGC, CO and NO_x in heaters using liquid and gaseous fossil fuels.	No	No	No

ENVIRONMENTAL ASPECT/ PRODUCT POLICIES	Energy efficiency	Energy consumption (or energy losses)	Air emissions	Technical requirements influencing environmental aspects	Presence of hazardous substances	Sound power level
Regulation 1187/2015 with regard Ecodesign on solid fuel boilers and packages of a solid fuel boiler, supplementary heaters, temperature controls and solar devices	Energy efficiency index (EEI)	Auxiliary energy consumption included in the EEI	No	No	No	No
Regulation 1185/2015 with regard to Ecodesign requirements for solid fuel local space heaters	Seasonal space heating efficiency	Auxiliary energy consumption included in the seasonal space heating efficiency	PM, OGC, NO_x in heaters using liquid and gaseous fossil fuels.	No	No	No
Regulation 1188/2015 with regard to Ecodesign requirements for local space heaters	Seasonal space heating energy efficiency	Auxiliary energy consumption included in the seasonal space heating efficiency	NO_x in heaters using liquid and gaseous fossil fuels.	No	No	No
Regulation 1186/2015 with regard to the Energy Labelling of local space heaters	Energy efficiency index (EEI)	Auxiliary energy consumption included in the EEI	No	No	No	No
Regulation 206/2011 with regard to Ecodesign requirements for air conditioners and comfort fans	Energy efficiency	Power consumption in off-mode and standby mode	Certain GHG penalize the energy efficiency	No	No	Indoor sound power level

ENVIRONMENTAL ASPECT/ PRODUCT POLICIES	Energy efficiency	Energy consumption (or energy losses)	Air emissions	Technical requirements influencing environmental aspects	Presence of hazardous substances	Sound power level
Regulation 626/2011 with regard to Energy Labelling of air conditioners	Seasonal energy efficiency ratio and seasonal coefficient of performance (all air conditioners except double and single ducts). Rated energy efficiency ratio and Rated coefficient of performance for double and single ducts air conditioners.	Hourly energy consumption	No	No	No	Indoor sound power level
Regulation 1253/2014 with regard to Ecodesign requirements for ventilation units	Thermal efficiency Fan efficiency	Specific energy consumption	No	Multi-speed drive or variable drive (except in dual use units). Thermal by-pass facility in bidirectional ventilation units. Filter equipped with visual change warning signal. Heat recovery system in non-residential ventilation units.	No	Sound power level
Regulation 1254/2014 with regard to Energy Labelling of residential ventilation units	Specific energy consumption	Maximum flow rate	No	No	No	Sound power level

Table 8 shows that Ecodesign regulations on HVAC systems set minimum thresholds mainly on energy efficiency, air emissions, sound power levels and other influencing technical requirements. The Energy Labelling just provides information on aspects such as the energy class, the annual energy consumption or the sound levels among others. On the other hand, GPP and EU Ecolabel have been defined aside the Ecodesign and Energy Labelling Directives and this is mainly due to their voluntary basis. Then, their product groups have different scope than those in Ecodesign or Energy Labelling since they aim at rewarding the best products in the market (which could be very different from those being obsolete or needed to be updated). In summary, Ecodesign and Energy Labelling Directives focus mainly on the use phase, although the recent EU Action Plan for a Circular Economy (EC, 2015a) called for more systematic integration of material efficiency aspects in product policies. In this regard, GPP and EU Ecolabel criteria give importance not only to the use phase, but also the manufacturing or end-of life (EoL) phases and additional environmental criteria such as content in hazardous materials.

2.6 Conclusions of the SoA

Implementing life cycle thinking, i.e. focusing on the most impacting phases, in the early stage of design is crucial to minimise environmental impacts along the life cycle of products. Simple environmental assessment methods are suitable for product and system design.

Regarding engineering systems, both top-down (from systems to products) and bottom-up (from products to systems) approaches are important for system analysis. Then, although the system approach is decisive for analysing system performance parameters, it could also be useful to analyse how the elements influence the whole system through decomposing the system into smaller parts (e.g. sub-systems, components).

Buildings are complex engineering systems and its analysis and design is a challenging task. On the one hand, HVAC systems are part of the bigger system ‘building’ and on the other hand, they are composed of many sub-systems and components. The performance of buildings greatly depends on the decisions made in the design phase (Annunziata et al., 2016).

In particular, the performance of HVAC systems is influenced by aspects of the building. A good HVAC system is that one which consumes little non-renewable energy. There are simulation tools for predicting the energy performance of buildings which include HVAC systems, but most are used once the building is constructed and the HVAC components installed, and not at the design phase. Anyhow simulation tools could be accompanied by simplified design tools earlier in the design process, to be able to give useful and quicker information for practical decision-making. Therefore, a method could be simplified and still support design activities.

Energy consumption has not only an environmental importance but also a great economic impact on users and nations. Thus, there are few environmental legal

requirements (e.g. Ecodesign and Energy labelling Directives) that manufacturers should meet regarding the energy efficiency of products. In addition, Member States of the EU should meet specific building energy requirements according to EPBD.

Product policies aim at making the EU market more sustainable. The Ecodesign and Energy Labelling Directives (EC, 2009; EC, 2010b), Green Public Procurement (GPP) (EC, 2008b) and the EU Ecolabel (EC, 2010c) represent the variety of performance levels of real products available in the market. Thus, such performance figures of products are available and of easy access for designers.

These products policies have dealt with the particularities of motor systems, lighting systems and heating systems. All these product policies apply the product approach, the extended product approach including the package concept or the system approach. However, the progress done by product policies in adopting a more system approach is limited since these are product-based and do not comprehensively consider system aspects.

Scientific literature in environmental assessments of HVAC systems focuses in the use phase and concludes that the energy consumption should be minimised for improving the environmental performance along the life cycle of these systems. Environmental aspects of EU product policies of HVAC systems include different environmental aspects along the life cycle of products. However, HVAC components are ErP so that their main environmental and economic impact is caused by the energy consumption. All the products groups affected by such policies have thresholds on their energy efficiency, among others (emission to atmosphere, sound levels, power, etc.).

Next section discusses the main findings in the literature review (section 2) in order to identify specific method requirements (section 3).

3. DESIGN METHOD REQUIREMENTS

3.1 Research methodology of the dissertation

My work at the Joint Research Centre (JRC) of the European Commission inspired the PhD topic. My job consisted of giving technical and scientific support to the development of environmental product policies such as Ecodesign and Energy labelling Directives on certain ErP (windows, commercial refrigerators and taps and showers). I contributed to the Preparatory Studies of several product groups which represent the basis for the development of Ecodesign and Energy labelling requirements. In particular, I worked in the development of a methodology for assessing environmental impacts during research and development phase of innovative windows (Allacker et al., 2013). In the case of the Preparatory Study of taps and showers (Cordella et al., 2014) I carried out the environmental and economic analysis of different base cases and design options through MEErP[1] methodology/tool (Kemna, 2011). In addition, I worked on the system approach of taps and showers and on the policy mix alternatives of this product group. Regarding commercial refrigerators, I contributed to the analysis of the end-of-life of this product group: a policy report (Moons et al., 2014) and one derived scientific paper (Ardente et al., 2015). I also had contact with industry (through stakeholder meetings and visits to industry) since stakeholders are relevant players in the policy process development. This way I acquired the knowledge to do the policy analysis. Furthermore, working with such ErP, stimulated my concern on the importance of taking into account system aspects in environmental assessments.

Therefore, I decided to develop a method to assess and improve product's systems. During my job at the JRC I had seen the policy success on improving the environmental impacts of products and I thought this could be useful at a design level. For this reason, on the one hand, the idea was that such method could be useful for designers of systems and this explains my integration into G-SCOP laboratory. On the other hand, I wanted to link the method to policy as much as possible. The next step was to reduce the scope of the products included in the method. I chose HVAC systems because many of the components of such systems were regulated by European sustainable product policies. However, the scope of HVAC systems was still too broad since these systems deliver very different services and some components are very service-specific. The choice of heating systems was done according to its relevance inside the HVAC systems and because I had easy access to a real case study with heating components as well as to EU policy data for some components

Then, I carried out an extensive literature review which was based mainly on analysing scientific papers and technical and legal reports from relevant

[1] Methodology for Ecodesign of Energy-related Products

organisations (European Commission, associations of manufacturers, standardisation bodies, etc.). There is huge scientific, technical and legal information on HVAC systems. There are also plenty of scientific papers on environmental assessment of HVAC systems. However, little but relevant information was found on how HVAC systems are affected by building regulations. No scientific information was found in the particular topic of environmental product policies since many of these regulations are quite new and they have being recently implemented by manufacturers. However, there are some technical and legal reports on this topic.

The usual (and indispensable) approach is that engineering is used for policy development. This is obvious since policy needs to be applicable to real engineering systems. Likewise, market analysis is useful to investigate how industry behaves and to ensure the compliance of realistic legal requirements. However, no information was found on the approach of policy being useful for engineering.

Then I started developing a simplified method that would be useful for engineers, that supported design activities at system level, and which enhanced informed decision-making on multiple design solutions based on different configurations of devices currently available on the market and regulated by product policies.

Once the method was drafted, I decided to test it in a real case study. The method was tested in the solar water heating and space heating systems of my rented house of Ispra (Italy) because the landlord had been the installer of the heating systems of the dwelling so that I had easy available information and the technical support I needed. The application of the method in the case study helped to structure and to polish the method.

Finally, in order to enrich the thesis topic, I analysed in detail the system approach of European environmental product policies, in the particular case of the package concept of the Energy Labelling Directive of heating devices (section 6).

To sum up, the research has been carried out through different means:

- Involvement on policy development and analysis of technical documents used to support policy making at the EU level;
- Literature review on engineering systems, environmental assessments in HVAC systems, heating systems and product policy;
- Creating a method to be used by industrialists/practitioners which used policy data;
- Testing of the method on a real case study and improvement of the method.
- Analysis of the ‘package concept’ of heating systems of product policies.

3.2 Discussion of the SoA

The aim of this section is to discuss some issues of the SoA and to summarise main findings in order to identify requirements for a method that could be used by designers of heating systems.

3.2.1 How to design good performing HVAC systems

The design of efficient HVAC systems is a huge challenge since buildings are complex systems. When designing HVAC systems, the choice of products to be installed is usually made with regard to load calculations (Harish and Kumar, 2016). The optimisation of building design is still a topic of research and has yet to be implemented in engineering (Attia et al., 2013). Thus, in order to improve the energy performance of residential buildings, the building needs to be considered as a whole rather than as its individual components, and the solutions should be more flexible and user-friendly than those currently used (De Boeck et al., 2015). The usual design procedure of HVAC systems focuses mainly on satisfying heating demands, while system optimisation is considered secondary (Randaxhe et al., 2015; Attia et al., 2013). System optimisation can be achieved at two different levels, in terms of energy efficiency performance and of low-emission performance (Fesanghary et al., 2012). The low-emission performance does not include the energy input from renewable sources since they reduce the use of non-renewable energy sources. Optimisation at system level should be then regarded as a key aspect of a method capable to be used by engineers and building designers.

But how to know if a HVAC system is well designed or not? Is it better or worse than alternative systems? Energy benchmarking of systems engineering consists in comparing the energy performance of a system against a common metric that represent the optimal performance of a reference system (Key et al., 2013). Product policies use benchmarking in order to set which is the average performance level of the majority of products in the EU market. This is needed in order to set thresholds (e. g. Ecodesign Directive) able to be fulfilled by most manufactures. Once the market is known, the bad players can be eliminated through the Ecodesign Directive, the Energy Labelling Directive can pull the market towards the better products and the GGP and EU Ecolabel can award the best performing products. Thus, the benchmarking of systems would aid to know how good a HVAC system design is.

3.2.2 Environmental assessments on HVAC systems: scientific literature versus product policies methodologies

The analysed scientific literature (section 2.4) focuses mostly in holistic environmental assessments such as LCA. Usually, all the phases of the life cycle of HVAC systems are considered, although results demonstrate that the use of energy during the use phase is by far the most important impact of these systems. Instead, criteria of EU product policies (section 2.5.2) focus mainly on the use phase. Concerning energy efficiency, specific methods for analysing the energy performance of different product groups have been developed in these product policies. Anyhow, for HVAC products, the energy performance figures during the use phase, as delivered by the product policies, seem to be very related to environmental impacts on the life cycle (as demonstrated in the scientific literature review). Thus, the methods for assessing the energy performance at system level of products policies

are contributing to reduce the energy consumption, the most relevant environmental aspect of the life cycle of HVAC systems.

Some methods used by product policies to calculate the performance of the HVAC products may include very different technologies such as the water heaters run with different types of fuels (EC, 2013b; EC, 2013c). This might create a loss of accuracy in the figure provided, In contrast, it helps consumers to make fair comparisons between different products providing the same service. In addition, customers and users are provided with homogenous and easy-to-understand ratings. On the other hand, although not all types of products, especially the innovative ones, have developed EU product policies through specific product groups, EU product policies cover the most share and the most important types of HVAC products of the current market. Then, we could say that the majority of the products generating HVAC services on the market can be classified in some of the product groups in the scope of the product policies. This could be useful for designers in order to make choices of products available in the current market.

The methods used to measure the performance and the associated thresholds (updated regularly) of the product groups are usually developed during the 'Preparatory Studies', taking into account the currently or soon-to-be available technologies of the European market. These methods might not be purely scientific but they have been agreed and recognised by stakeholders (industry, government, consumer organisations, etc.) involved within the product group under study. Such methods are well known, implemented and agreed by manufacturers so that suitable for designers for making fair comparisons of products.

The four product policies (the Ecodesign and Energy Labelling Directives GPP and the EU Ecolabel) have facilitated the disclosure of very relevant information regarding product performance (Calero-Pastor et al., 2014). While the Ecodesign Directive sets minimum performance thresholds, the different energy classes reflect the variety of product performance levels currently available on the market, and GPP and the EU Ecolabel represent excellence in the performance of products. Thus, this batch of EU product policies could be seen as a mirror of the current market characteristics. In addition, the rapid evolution of technology hinders the dynamic and up-to-date knowledge of markets by designers. When technology evolves very quickly, some products are improved as others become obsolete over a short period of time. The use of EU product policies by designers avoids them to be continuously updated on the current market availability of products.

Then, the valuable information that EU product policies provides on the energy efficiency of ErP products could help to:

- Lean on a reliable and agreed scheme that is already available and easily accessible at the design step and useful in making fair comparisons of products.

- Assess system performance based on the different performance levels of products currently or soon-to-be available on the market.
- Identify the possible alternatives regarding the combined performance of the products that make up the system.

Otherwise, the common extended product approach considered in the product policies is less appropriate than the one considered in the scientific literature. This is mainly for two reasons. Firstly, this is because there are system components which cannot be considered as isolated products but as sub-system (i.e. distribution components in a HVAC system), and it is unlikely that they could be ever regulated by product policies in the near future. Thus, the extended product approach of product policies is susceptible of excluding some system components. The second reason is that product policies will hardly consider interactions between system components if some components could be left aside. In conclusion, the top-down approach (from systems to products) considered in the scientific literature is more appropriate and could be easily integrated in a design method. Once the system has been defined, this approach is still compatible with the bottom-up approach (from products to systems) used by product policies at product level, as claimed before. Then, different levels of product performance levels could be combined to obtain an optimal solution at system level.

Therefore, the method will firstly consider the system as whole in order to include system aspects. Secondly, the method will use EU product policies information (at product level). When this is not possible, designers would be able to choose alternative tools to calculate the performance of the system components.

3.2.3 Method requirements

Method requirements have been identified from the SoA (see conclusions in section 2.6) and the previous discussion (sections 3.2.1 and 3.2.2). The requirements of the method can be summarised as follows. The method should:

1. Be a simplified method to be useful in the design phase.
2. Adopt an approach ‘from system to products’ for modelling the system. In addition, the approach ‘from products to system’ should be used to calculate the system performance in order to see how the products affect the overall system.
3. Establish the reference benchmark system with which compare solutions.
4. Use easily accessible product information from EU product policies (whenever possible).
5. Allow engineers to use their preferred alternative methods when appropriate.
6. Facilitate decisions to optimise performance at system-level from product performance information available on the market.

4. DESIGN METHOD AND CALCULATION TOOL PROPOSAL

The aim of the method is to support the design of good performing heating systems in residential buildings throughout the right combination of the performance levels of the systems components. It is a simplified method since combines concept design at hand (the method itself and design of energy flows) with the use of simple equations (calculation of energy parameters) and/or building simulation tools (optional).

The method uses the two system approaches identified in the literature review (section 2.2). It first models the system from a top-down approach and secondly, it calculates its performance from a bottom-up approach. Then, the geographical context, the building envelope and the user behaviour are considered in the method as well as the technology of the components of the heating system.

The method is based on energy benchmarking of systems. The benchmark system is defined in this manuscript as the system that uses components with average performance levels. Then, a good performing system is a system that is behaving better than a benchmark system. The method consists firstly, in estimating the performance of one reference heating system (the benchmark in the case of a new design or the current system in the case of a re-design). Secondly, several improved alternatives are proposed and compared with the reference heating system. The designer is then able to choose among the different solutions provided.

The method uses data of different EU product policies of the products composing a heating system. Then, for instance, a system component with just Ecodesign minimum requirements might be combined with other components with a certain energy label or compliant with GPP or EU Ecolabel criteria. When EU product policy data is not available, the method allows engineers to use their preferable sub-methods to establish the performance of such product.

In principle, the method assumes that the performance of one component is independent from the performance of another component. However, the method is flexible enough to consider possible interdependencies at the system level.

The implementation of the method in the design or re-design of a heating system will allow to:

- quantify the relative importance of individual components with different performance levels in the overall system energy performance;
- determine how good a heating system is;
- deliver combinations (design alternatives) of different levels of components performance for specific saving targets.

The estimation of the system performance in the method is done through a calculation tool that assesses the energy performance parameters. The energy performance parameters are explained in next section 4.1, the procedure of the method in section 4.2 and the calculation tool in section 4.3.

4.1 Energy performing parameters

The method relies in the analysis at system level of four performing parameters interrelated among each other. The relevance of these parameters has been highlighted in section 2.3. The definitions of these parameters in this dissertation are:

- Energy heating demand (E_{Demand}): is the energy useful for delivering sanitary hot water or space heating. In order words, it is the output energy provided by the system;
- Non-renewable energy (NRE) consumption ($E_{NRE\ Consumption}$): is the NRE consumed (or lost) by the different components of the system needed to provide the service. It is the non-renewable energy input entering the system;
- Energy losses of the system (L): are the sum of the energy losses of all the components of the system;
- Low-emission energy efficiency (η): is the ratio between the energy heating demand and the NRE consumption.

They are calculated with the calculation tool (section 4.3).

The main objective of the design of a good or optimised heating system is to minimise the NRE consumption. This could be done either by reducing the energy demand or the energy losses, or by increasing the input of renewable energy (RE) or the energy efficiency of the components.

Then, it could happen that components were performing poorly from an energy efficiency point of view when using high amount of RE. The analysis of the energy losses provides additional information on the behaviour of the system components regardless the type of energy used (renewable or non-renewable). Thus, it is also important to minimise the components' energy losses. This way, the practice of using mainly RE sources in order to compensate low performing components can be avoided. Even in the case of using only NRE, the analysis of the relative importance of energy losses of components into the overall losses of the system is useful to identify components with the highest contribution to losses.

The minimisation of the energy heating demand might be also achieved through the use of certain technology such as components abled to save energy at the user point, such as taps and showers or temperature controls. This would allow minimising also the overall energy consumption.

In conclusion, the aim of a good heating system design is to minimise the NRE consumption, but the analysis of the energy losses and energy efficiency of the components is also important to understand how the system behaves. In addition, components which are able to modify the energy demand should be also regarded. These four parameters are used to analyse the system at the five steps of the method which will allow designers to take decisions on which parameter to optimise more or less.

4.2 Procedure of the method

The assessment method uses a calculation tool to obtain the energy demand, energy losses, NRE consumption and the energy efficiency of the heating system from the performance figures of its components. It focuses on the components composing the system and the best configuration of components in order to optimise the system performance. The method includes five steps of assessment (Table 9) divided in two main phases, the diagnostic of the initial system and the improvement phases. The calculation tool is used in each step of the method, except in step 1.

Table 9 Overview of the method

METHOD		CALCULATION	OUTCOMES
Phase 1: Diagnostic of the initial system	Step 1. Set of the global context and system modelling	Definition of the geographical context, the building features, the user behaviour and the heating system model.	A particular global context is defined and the heating system is modelled (types of components and their interactions are set).
	Step 2. Estimation of the performance of the initial system (the benchmark in the case of a new design or the current system in the case of a re-design).	✓ Energy heating demand ✓ Energy losses ✓ NRE consumption ✓ Low-emission energy efficiency ...of the initial system	Reference system with which compare next results.
	Step 3. Study of the influence of relevant individual components in the overall system.	✓ Energy heating demand ✓ Energy losses ✓ NRE consumption ✓ Low-emission energy efficiency ...of the system when improving one by one (independent and relevant) component.	Relevant components with the highest system improvement potential (savings in kWh/y).
Phase 2: Improvement: investigation of a better performing system	Step 4. Analysis of the worst, benchmark and best systems.	✓ Energy heating demand ✓ Energy losses ✓ NRE consumption ✓ Low-emission energy efficiency ...of worst, benchmark and best systems	Combination of components' performance levels with the worst and best feasible solutions. Comparison with the benchmark and the current design systems. How good is my initial system?
	Step 5. Analysis of other feasible alternatives	✓ Energy heating demand ✓ Energy losses ✓ NRE consumption ✓ Low-emission energy efficiency ...of different improved solutions	Energy performance parameters of combinations of different components' performance levels. Multiples solutions for certain energy saving's target.

4.2.1 Phase 1. Diagnostic of the initial system

4.2.1.1 Step 1. Global context and system modelling

The performance of a heating system depends on the performance of its components, its interactions with the building, the geographic context (climatic data, local conditions of the building, etc.) and the user behaviour. The geographical context, the building envelope and the user behaviour define the energy demand. The method recommends all these variables to be accurately taken into consideration at the early stage of the design process.

The purpose of a heating system is to provide sanitary hot water or space heating to the dwelling. As stated in section 2.2, the heating system is composed of components with different sub-functionalities (CEN, 2006): the energy generation, the storage, the distribution, the delivery of the service and the controls. To classify the products of the system according to these functionalities guarantees the inclusion of all the products and/or sub-systems, and thus to not to miss any. In addition, this product classification facilitates the task of grouping some products on the designer's choice in order to adapt the model to the tools which will be used later to calculate or collect product or sub-system performances.

Therefore, firstly, the global context is detailed and secondly the heating system is modelled through the description of the system's components, how they are or can be connected, their sequence and main heat flows among them. Figure 4 summarises the general global context and the system modelling.

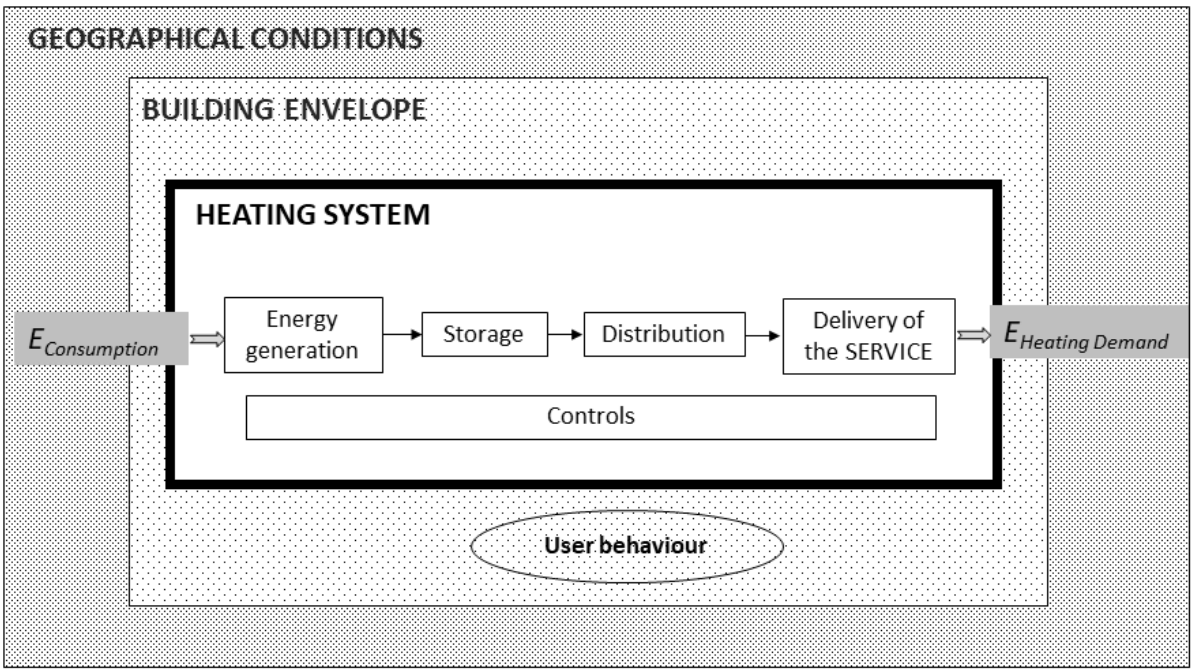


Figure 4. General heating system model within the global context

4.2.1.2 Step 2. Estimation of the performance of the initial system

The objective of this step is to estimate the performance of a reference heating system that will be used to compare with the improved solutions assessed at next steps.

In a new design, the initial system analysed will be the benchmark system. The benchmark system is created using average performance levels (in the market) of the components composing the system. In a redesign, the current performance of the components of the system is used for determining the initial system.

In this step, the calculation tool is used for the first time. Results of this step deliver the figures of the energy heating demand, NRE consumption, energy losses and low- emission energy efficiency of the initial system. These parameters calculated at this step 2 are used to compare with those ones calculated at the next steps.

4.2.1.3 Step 3. Study of the influence of relevant individual components in the overall system.

The aim of this step is to identify the relevant components and the most influencing components in the overall system.

Firstly, relevant and non-relevant components of the system are identified by designers' own judgments. Relevant components are those ones that have a significant and feasible improvement potential. This should be assessed by the designer according to the specific options and limitations of the heating system under study. The non-relevant components will be excluded for this and further improvement analysis.

Secondly, the range of performance levels of each relevant component is analysed (from best to worst) according to the EU product policies affecting the component. Ideally, the best components are represented by performance levels of GPP and EU Ecolabel criteria or by the highest energy classes. Intermediate performance levels of components would be defined through the different Energy Labelling classes. Finally, the worst components performance level would be that one regulated by minimum Ecodesign requirements (or the lowest energy label). In the case a component in the system is not affected by any European regulation, other sources (national regulations, standards, certifications, other ecolabels, etc.) could be used. In addition, even designers could made assumptions on the range of performance levels when EU product policy data is not available. This analysis will deliver the performance levels of each component under study, available in the current market (Table 10).

In principle, the type of technology of each component is assumed to be equivalent (the same sub-function inside the system) at each performance level, so big changes in technologies which could make change the way the system has been initially modelled (step 1) are not contemplated.

Table 10 shows an example on how the performance levels (in terms of efficiency or losses) are set for a generic component i, with a maximum performance level A and a minimum performance level H. IS stands for Initial System and represents the performance level of the initial system assessed in the previous step (step 2, section 4.2.1.2).

Table 10. Performance levels of a component i

LEVEL OF PERFORMANCE (from best to worst)	Component i
EU Ecolabel or highest energy label (A)	= η_{1A} or L_{1A}
GPP or energy label (B)	= η_{1B} or L_{1B}
Energy label (C)	= η_{1C} or $L_{1C\ (IS)}$
…	= η_{1}… or L_{1}…
Ecodesign requirements or lowest energy label (e.g. H)	= η_{1H} or L_{1H}

Examples of specific components performance levels can be found in Table 21, Table 22, Table 23, Table 24 and Table 25. However, not all the components may have the same number of performance levels (Table 11).

Table 11. Example of performance levels of n components assessed at step 3

	LEVEL OF PERFORMANCE							Number of performance levels
Component 1	A	B	C (IS)	D	E	G	H	$m_1 = 7$
Component 2	A	B (IS)	C	-	-	-	-	$m_2 = 3$
Component 3	A (IS)	B	C	D	E	-	-	$m_3 = 5$
Component n	A	B	C	D (IS)	-	-	-	$m_n = 4$

Once the performance levels of each relevant component are set, the calculation tool is run for each performance level identified for each component of the system. The performance level is modified one at a time and the rest of the components performance levels are left as in the initial system (step 2, section 4.2.1.2). Equation 2 shows the total number of combinations or systems created (SC) of each performance level of each component, where mi is the performance level of component i.

Equation 2

$$SC\ (Step\ 3) = \sum_{i=1}^{n} mi$$

In the example shown in Table 11, the total number of systems created would be 19 (7+3+5+4).

Results of step 3 show the influence of individual components (from worst to best) for all their performance levels identified in the overall system, in terms of energy improvement potential (savings in kWh/y), where zero improvement is equal to the initial system assessed at step 2 (section 4.2.1.2). Thus, components with the highest improvement potential in terms of NRE consumption are identified.

4.2.2 Phase 2. Improvement: investigation of a better performing system

The objective of this phase is to aid the designer to choose improved solutions (with respect the initial system) by analysing how different combination of components performance levels can optimise the system.

4.2.2.1 Step 4. Analysis of the best, benchmark and worst systems.

The objective of this step is to determine how good the initial system is and to quantify the improvement potential at system level.

Worst, benchmark (in case it is not the initial system) and best systems are proposed through the combination of components performance levels according to results of step 3. The best system is estimated choosing the best feasible performance levels of relevant components. The benchmark system is estimated choosing average performance levels of relevant components. The worst system is estimated choosing the worst performance levels of relevant components (step 3, section 4.2.1.3). The calculation tool is used to generate results of best, benchmark and worst systems.

Results of this step 4 deliver the figures of the four performing parameters (section 4.1) for the best, benchmark and worst feasible alternatives. Then, best, benchmark and worst combination of components performance levels are compared with the initial system obtained at step 2 (section 4.2.1.2).

4.2.2.2 Step 5. Analysis of other feasible alternatives.

This step aims at analysing other improved combinations of components performance levels not studied in the previous steps.

At this step, each better (than the initial system) and feasible level of performance for each relevant component identified at step 3 are combined one-by-one within the

different components creating several design alternatives. Later, these are assessed with the calculation tool.

Table 12 shows an example on how the number of performance levels is reduced by choosing only the better and the feasible (e.g. performance level A for component n is not feasible) performance levels.

Table 12. Example of performance levels assessed at step 5

	LEVEL OF PERFORMANCE							Number of performance levels (Step 3)	Feasible and better performance levels (Step 5)
Component 1	A	B	C (IS)	D	E	G	H	$m_1 = 7$	$l_1 = 3$
Component 2	A	B (IS)	C	-	-	-	-	$m_2 = 3$	$l_2 = 2$
Component 3	A (IS)	B	C	D	E	-	-	$m_3 = 5$	$l_3 = 1$
Component n	-	B	C	D (IS)	-	-	-	$m_n = 4$	$l_4 = 3$

Equation 3 shows the total number of combinations of performance levels of different components (systems created), where li is the total number (including the initial system) of feasible and better performance levels of component i.

Equation 3:

$$SC\ (Step\ 5) = \prod_{i=1}^{n} l_i$$

In the example shown in Table 12, the total number of systems created would be 18 (3·2·1·3).

Results of this step 5 show the different performing parameters of all the selected combinations of components performance levels. Then, for a certain saving or energy efficiency target, many alternative solutions might be possible.

4.3 The calculation tool

A calculation tool to support the deployment of the method has been developed. It aims at guiding the calculation of the performing parameters: energy demand, NRE consumption, energy losses and the energy efficiency at system level (section 4.1).

The tool consists in a simplified procedure to calculate the energy parameters of heating systems, based on the performance levels of its components using data coming from EU product policies or other regulations/sources.

The tool for calculating the performing parameters has three steps:

1. Calculation of energy heating demand (E_{Demand});

2. Calculation of energy losses (L) and NRE consumption ($E_{NRE\ Consumption}$):
    a. Compilation of components performance levels using available figures of EU product policies and/or if necessary calculate or collect them with other tools;
    b. Calculation of the energy flows of the system;
3. Calculation of the low-emission energy efficiency (η).

Figure 5 shows two examples on how the calculation tool is used within the method: the performance of the initial system (step 2) and the performance of relevant component 1 (first assessment of step 3). Firstly, the information set in step 1 of the method (climate conditions, building envelope, user behaviour, etc.) are used to calculate the energy demand. Next, the energy losses are assessed and the NRE consumption calculated from the figure of the energy demand throughout the modelled system (information from step 1 of the method). Finally, the low-emission energy efficiency of the initial system (step 2 of the method) is calculated based on the energy demand and the NRE consumption figures. Likely, information from step 3 of the method is used to calculate the energy heating demand if needed (if not needed, information from step 1 is used), and from this figure, the rest of the energy performing parameters for a certain system in which only the performance of one component has been modified (component 1).

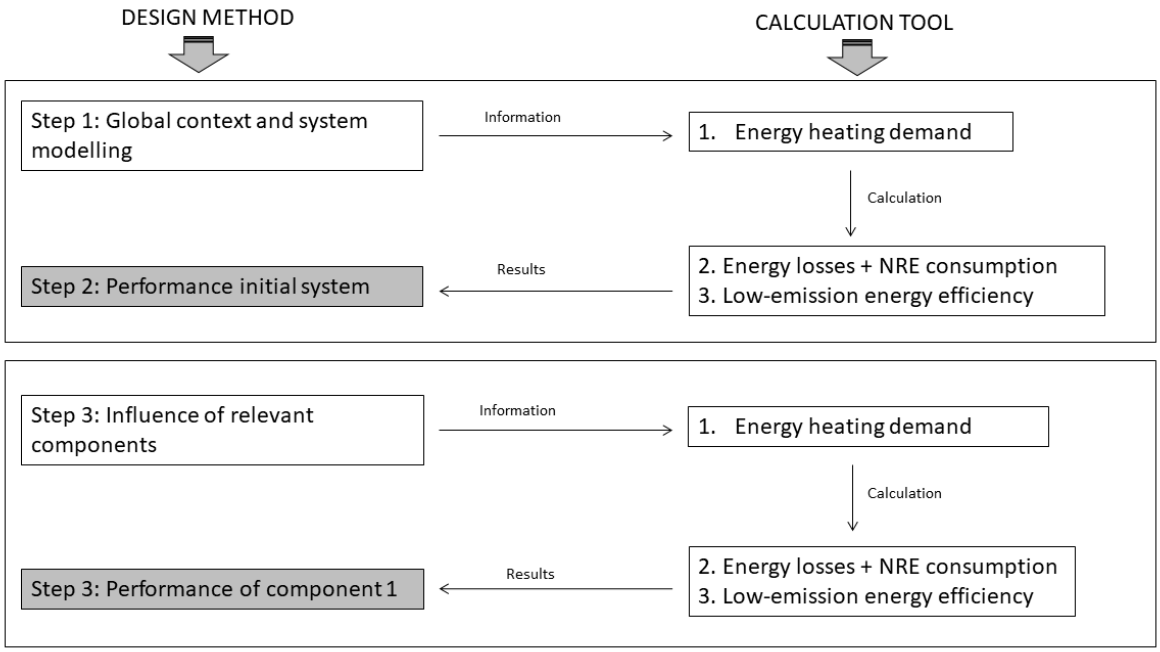


Figure 5. Inputs and outputs of the method and calculation tool

The calculation tool is run as many times (Figure 6) as systems are created.

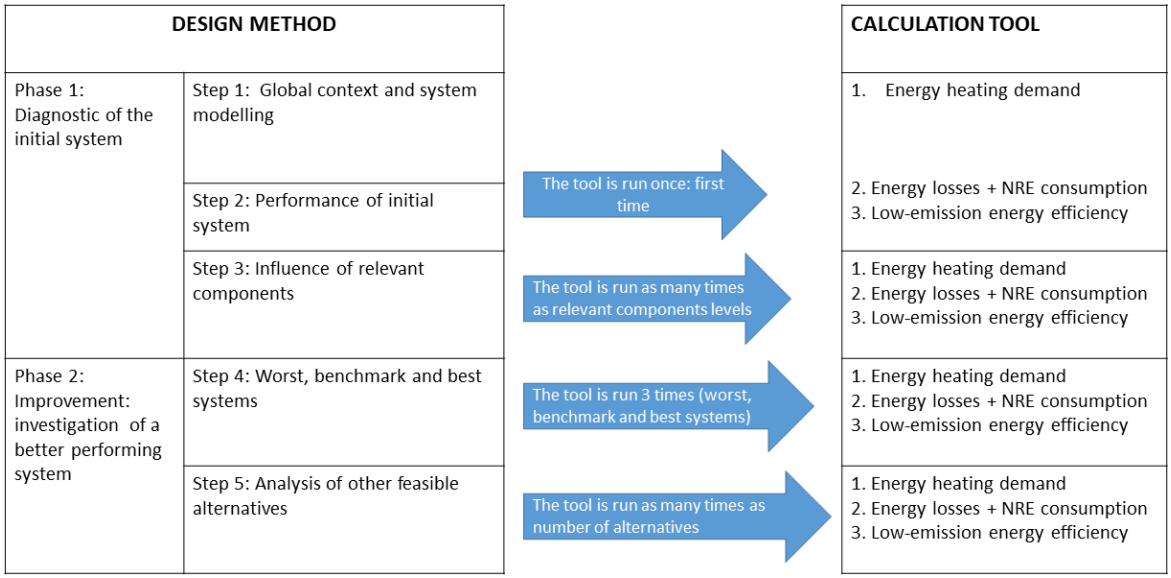


Figure 6. Relationship between the design method and the calculation tool

Table 13 summarises main systems assessed with the calculation tool according to each step of the method. In Table 13, n is the number of components in the system, IS refers to the performance level of the components of the initial system, m is the number of performance levels (from the best A to the worst H) of a component and l is the number of feasible and better performance levels of a component. System 1A means that component 1 has a performance level A and the rest of the components remain the same as in the initial system.

Table 13. Use of the calculation tool in the method

METHOD STEPS	SYSTEMS CREATED	COMPONENTS PERFORMANCE LEVELS	TIMES THE CALCULATION TOOL IS RUN
Step 2: Estimation of the performance of the initial system (section 4.2.1.2)			
First assessment with the calculation tool	Initial System (IS)	Comp. 1 = η_{1IS}	1
		Comp. 2 = η_{2IS}	
		…	
		Comp. n = η_{nIS}	
Number of systems created at Step 2 =			**1**
Step 3: Study of the influence of relevant individual components in the overall system (section 4.2.1.3)			
Influence of Comp. 1 in the overall system. Only the performance of component 1 is changed, the rest of components stay as the initial system.	System 1A	Comp. 1 = η_{1A} Rest comp = initial system (Comp. 2 = η_{2IS} and Comp.n = $\eta_{n\ IS}$)	1
	System 1B	Comp. 1 = η_{1B} Rest comp = initial system	1
	System 1H	Comp. 1 = η_{1H} Rest comp = initial system	1
Influence of Comp. 2 in the overall system. Only the performance of component 2 is changed, the rest of components stay as the initial system.	System 2A	Comp. 2 = η_{2A} Rest comp = initial system (Comp. 1 = η_{1IS} and Comp.n = $\eta_{n\ IS}$)	1
	System 2B	Comp. 2 = η_{2B} Rest comp = initial system	1
	System 2H	Comp. 2 = η_{nH} Rest comp = initial system	1
Influence of Comp. n in the overall system. Only the performance of component n is changed, the rest of components stay as the initial system.	System nA	Comp. n = η_{nA} Rest comp = initial system (Comp. 1 = η_{1IS} and Comp.2 = $\eta_{2\ IS}$)	1
	System nB	Comp. n = η_{nB} Rest comp = initial system	1
	System nH	Comp. n = η_{nH} Rest comp = initial system	1
Number of systems at Step 3 =			$\sum_{i=1}^{n} mi$

METHOD STEPS	SYSTEMS CREATED	COMPONENTS PERFORMANCE LEVELS	TIMES THE CALCULATION TOOL IS RUN
Step 4: Analysis of the best, benchmark and worst systems (section 4.2.2.1)			
Best performance	Best system (1A, 2A, nA)	Comp. 1 = η_{1A}	1
		Comp. 2 = η_{2A}	
		Comp. n = η_{nA}	
Benchmark performance (average performance of products)	Benchmark system (1B, 2B, nB)	Comp. 1 = η_{1B}	1
		Comp. 2 = $\eta_{2\,B}$	
		Comp. n = $\eta_{n\,B}$	
Worst performance	Worst system (1H, 2H, 3H)	Comp. 1 = η_{1H}	1
		Comp. 2 = η_{2H}	
		Comp. n = η_{nH}	
Number of systems created at Step 4 =			**3**
Step 5: Analysis of other feasible alternatives (section 4.2.2.2)			
Alternative 1	System 1A, 2B, nA	Comp. 1 = η_{1A}	1
		Comp. 2 = η_{2B}	
		Comp. n = η_{nA}	
Alternative 2	System 1B, 2B, nA	Comp. 1 = η_{1B}	1
		Comp. 2 = η_{2B}	
		Comp. n = η_{nA}	
Alternative 3	System 1C, 2B, nA	Comp. 1 = η_{1C}	1
		Comp. 2 = η_{2B}	
		Comp. n = η_{nA}	
Alternative 4	System 1A, 2C, nA	Comp. 1 = η_{1A}	1
		Comp. 2 = η_{2C}	
etc.		Comp. n = η_{nA}	
Number of systems created at Step 5 =			$\prod_{i=1}^{n} l_i$

Thus, the total number of systems created and assessed with the calculation tool would be:

Equation 4:

$$\text{TOTAL SC} = 1 + \sum_{i=1}^{n} mi + 3 + \prod_{i=1-h}^{n} li$$

4.3.1 Calculation of the energy heating demand of the dwelling

The calculation tool allows the practitioner to choose the most convenient instrument (simulation software, simple equations, rules of thumb, etc.) for calculating the energy demand. Simulation tools (eQUEST, DesignBuilder, SEAS3, etc.) are able to model the building envelope (closures, thermal bridges, etc.), the climatic data of the location and the user behaviour to obtain the energy demand of a dwelling. Simple equations could refer the energy demand to, for instance, floor area, number of inhabitants or consumption patterns. Another option is to use available figures on the energy demand of the dwelling, for example the ones available in energy certifications of buildings according to the EPBD (EC, 2010a).

4.3.2 Calculation of the energy losses and the non-renewable energy consumption

The calculation of the energy losses and the NRE consumption is done through the analysis of the energy flows of the system. However, firstly, information about the components is needed.

a) Compilation or calculation of the performance of every component or sub-system using EU product policies.

Firstly, components performance figures from EU product policies are compiled; either from real products (manufacturer's technical information) or from the regulations affecting the target product (implementing regulations on the Ecodesign or supplementing regulations on the Energy Labelling Directives, the EU GPP or the Ecolabel for specific product groups). If a component or sub-system does not fall within the scope of such product policies, then its performance can be calculated using other tools such as simulation tools, simple equations or rules of thumb (Table 14).

Table 14. Components' performance figures can be collected or calculated using EU product policies or other instruments.

SYSTEM COMPONENT	PERFORMANCE CALCULATION INSTRUMENT	COMPONENT PERFORMANCE FIGURE
Component 1	1st EU PRODUCT POLICIES - Ecodesign Directive - Energy Labelling Directive - EU GPP - EU Ecolabel	= η_1 or L_1
Component 2		= η_2 or L_2
…		…
Component n	2nd OTHER INSTRUMENTS - Simple equations - Rules of thumb	= η_n or L_n

b) Calculation of the energy flows of the system

This calculation is done based on the energy demand obtained previously (section 4.3.1). The energy efficiency of each component (η_{Comp}) can be used in Equation 5 to calculate the energy output or input of that component or the other way around. The energy losses of all components L_{SYSTEM} (Equation 7) are aggregated to the E_{Demand} in the opposite direction of the energy flow (Figure 7) to calculate the and from this figure, the $E_{Consumption}$ can be calculated (Equation 8). The sequence of the calculation of the energy consumption, through energy balances and inverse to the real energy flows (Figure 7) is the same as that applied in building simulation tools.

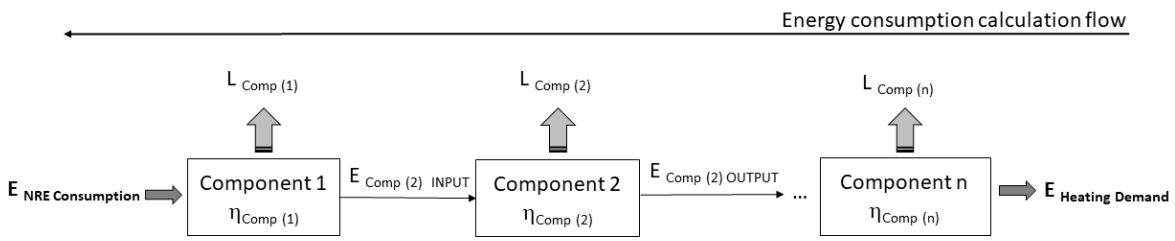


Figure 7. Energy flows of the heating system.

Equation 5:

$$E_{Comp\ (i)\ OUTPUT} = E_{Comp\ (i)\ INPUT} \times \eta_{Comp\ (i)}$$

Equation 6:

$L_{Comp\ (i)} = E_{Comp\ (i)\ OUTPUT} - E_{Comp\ (i)\ INPUT}$

Equation 7:

$L_{SYSTEM} = \sum L_{Comp\ (i)}$

Equation 8:

$E_{NRE\ Consumption} = \sum L_{Comp\ (i)} + E_{Demand}$

4.3.3 Calculation of the low-emission energy efficiency

The low-emission energy efficiency of the system is defined as:

Equation 9:

$\eta_{SYSTEM} = E_{Demand} / E_{NRE\ Consumption}$

Where E_{Demand} is the energy useful for the service to be delivered and $E_{NRE\ Consumption}$ is the energy that is consumed by the heating system and its different components to provide the service.

Only the NRE consumption is considered since building-related policies are oriented towards low-emission designs. Thus, when a RE source is used in the system, this RE is not included in Equation 9. In this case, the energy efficiency of Equation 9 aims at minimising the NRE consumption, which is also called the low-energy efficiency (see section 2.3).

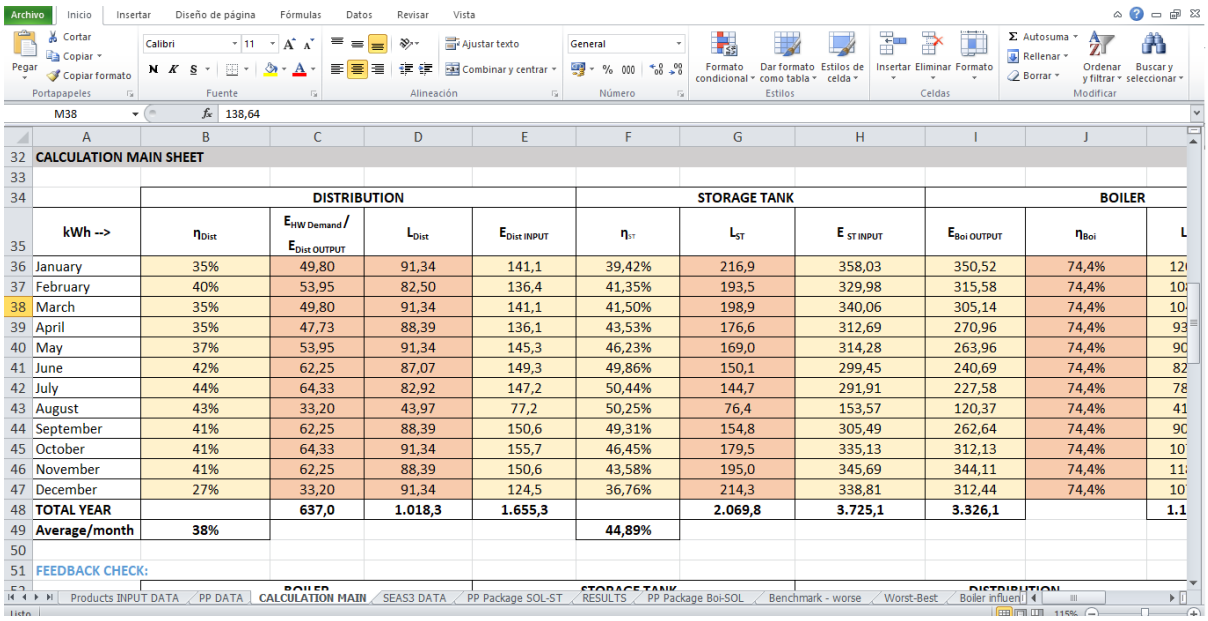
5. A CASE STUDY: RE-DESIGN OF A SOLAR SANITARY HOT WATER SYSTEM AND SPACE HEATING SYSTEM IN A DWELLING

The method proposed was tested in a real case study that provides sanitary hot water and space heating. The method is applied in parallel to the sanitary hot water system and the space heating system since they have different functionalities, although they both share a condensing boiler. In this section, the heating systems are redesigned in order to identify their most significant improvement potential.

5.1 Implementation of the method in the case study

5.1.1 Phase 1: Diagnostic of the initial system

For this particular case study, a calculation tool has been created in an Excel file in order to facilitate the multiple calculations on all the created systems. This Excel file contains several sheets to introduce the data from the products systems, according to product policies (when available), software, etc. It also has some sheets to make calculations and others which give overall results. Figure 8 shows the appearance of this Excel file. Note that in this case, calculations have been made per month.



CALCULATION MAIN SHEET

kWh -->	DISTRIBUTION η_{Dist}	DISTRIBUTION $E_{HW\ Demand}/E_{Dist\ OUTPUT}$	DISTRIBUTION L_{Dist}	DISTRIBUTION $E_{Dist\ INPUT}$	STORAGE TANK η_{ST}	STORAGE TANK L_{ST}	STORAGE TANK $E_{ST\ INPUT}$	BOILER $E_{Boi\ OUTPUT}$	BOILER η_{Boi}	L
January	35%	49,80	91,34	141,1	39,42%	216,9	358,03	350,52	74,4%	12
February	40%	53,95	82,50	136,4	41,35%	193,5	329,98	315,58	74,4%	10
March	35%	49,80	91,34	141,1	41,50%	198,9	340,06	305,14	74,4%	10
April	35%	47,73	88,39	136,1	43,53%	176,6	312,69	270,96	74,4%	93
May	37%	53,95	91,34	145,3	46,23%	169,0	314,28	263,96	74,4%	90
June	42%	62,25	87,07	149,3	49,86%	150,1	299,45	240,69	74,4%	82
July	44%	64,33	82,92	147,2	50,44%	144,7	291,91	227,58	74,4%	78
August	43%	33,20	43,97	77,2	50,25%	76,4	153,57	120,37	74,4%	41
September	41%	62,25	88,39	150,6	49,31%	154,8	305,49	262,64	74,4%	90
October	41%	64,33	91,34	155,7	46,45%	179,5	335,13	312,13	74,4%	10
November	41%	62,25	88,39	150,6	43,58%	195,0	345,69	344,11	74,4%	11
December	27%	33,20	91,34	124,5	36,76%	214,3	338,81	312,44	74,4%	10
TOTAL YEAR		**637,0**	**1.018,3**	**1.655,3**		**2.069,8**	**3.725,1**	**3.326,1**		**1.1**
Average/month	**38%**				**44,89%**					

FEEDBACK CHECK:

Figure 8. Screenshot of the MS Excel file created for the case study

5.1.1.1 Step 1. Global context and heating system modelling

The house is located in the north of Italy and the dwelling has a surface of 61 m^2. The house and its heating systems were refurbished in 2012.

Firstly, all the data required (location, building aspects, user behaviour, etc.) for the calculation of the energy demand is collected. In this case study, it was used the simulation tool SEAS3 (ENEA, 2014), recommended by the Italian Energy Agency. SEAS3 facilitates the calculation of the energy demand of the dwelling according to the geographical conditions (climate zone E according to Italian regulations), the

characteristics of the building/dwelling (surroundings, orientation, height, thermal bridges, windows, etc.) and the user behaviour (presence during the year, opening of the closures, etc.).

The dwelling includes a solar sanitary hot water system and a space heating system which share the same boiler (Figure 9). The solar sanitary hot water system consists of the boiler, a solar panel (2.06 m^2) with a glycol pump, a storage tank with two coils, a sanitary water pipe network, three taps and one shower. The space heating system includes the boiler, the distribution components, the underfloor heating and the controls. There are also components such as two expansion vessels, a mixer valve and a safety valve but they are not considered in the analysis since their energy losses are considered to be negligible.

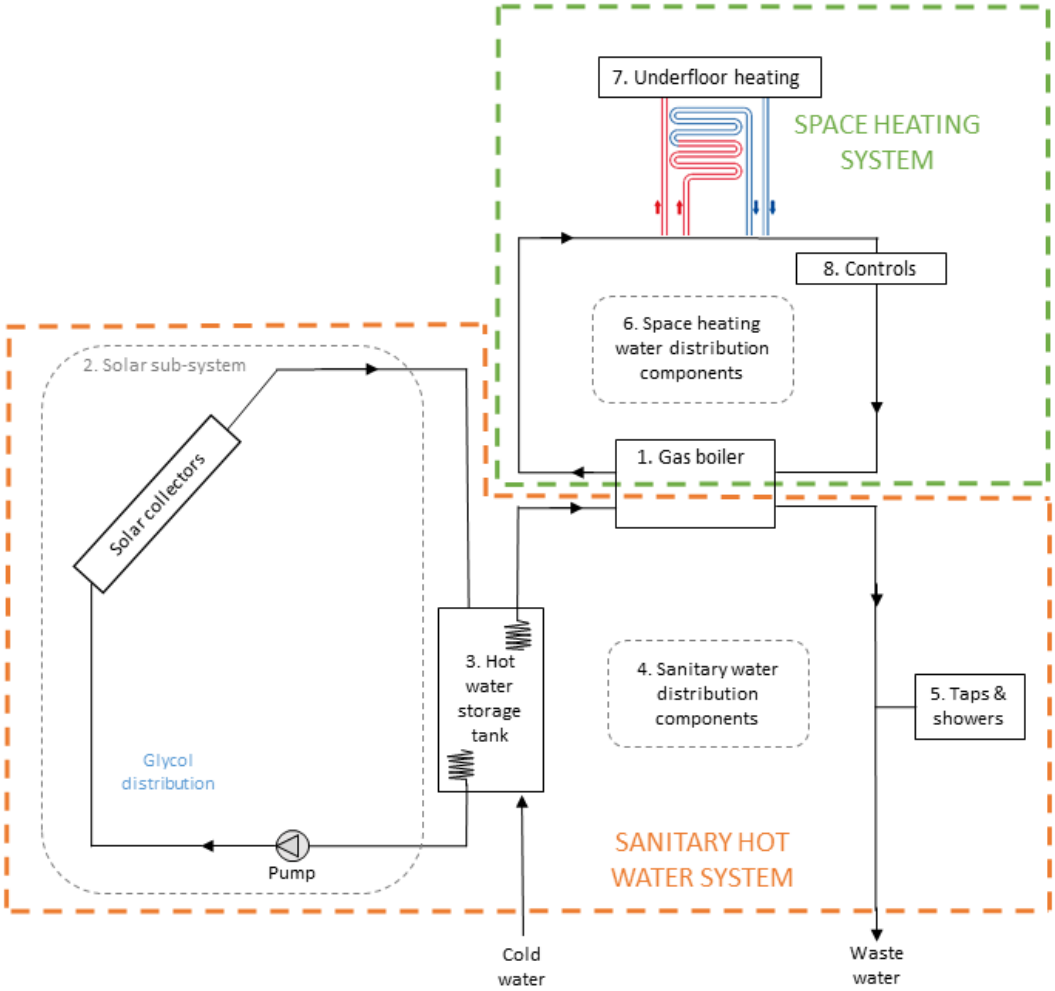


Figure 9. Heating systems of the case study.

In Figure 9 and Figure 10, the heating components (numbered from 1 to 8) are grouped according to their function in their overall system. The solar sub-system includes the solar panel, the distribution components of the glycol and the solar pump and has the function of generating RE. As mentioned, the boiler is the same for providing both sanitary hot water (HW) and space heating (SH) services.

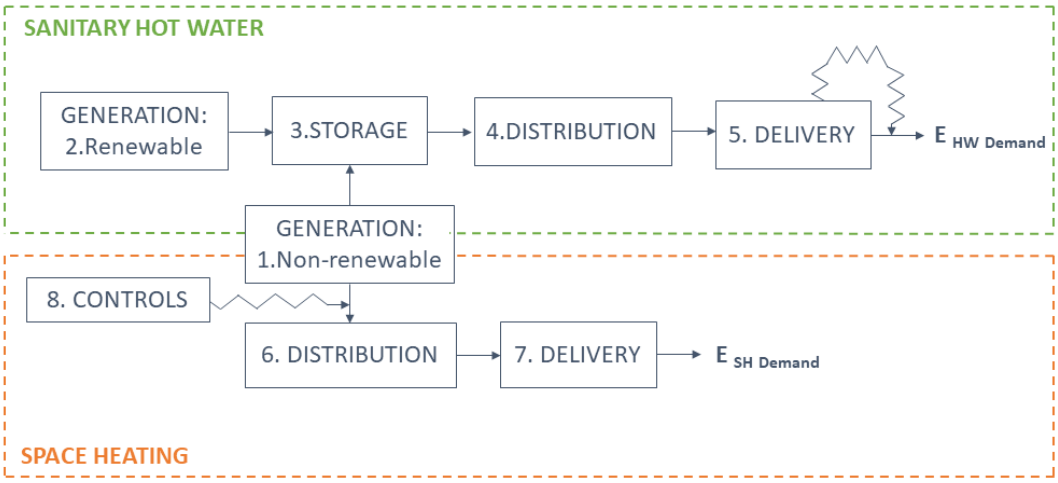


Figure 10. System modelling of the case study

According to EC 811/2013 (EC, 2013e), the boiler that provides both sanitary hot water and space heating is called a combination heater. Thus, these types of heaters are labelled twice since the energy efficiency is calculated through two different formulas; one for each function that deliver (sanitary hot water and space heating). This case study follows the same reasoning as in EC 811/2013, so that both functions are not interrelated. This is represented in Figure 10 by the 'GENERATION' component that contributies to both sanitary hot water and space heating.

The sanitary hot water delivery (taps and showers) and space heating controls (temperature control) components will be not considered as components directly involved in the energy flows of system (see zig-zag arrows in Figure 10). In the taps and showers, this is because these components modify the energy heating demand and not the previous energy flow from the distribution. In the case of the temperature control of the space heating system, the reason is that it is a component that has an indirect role in the system (the hot water used for space heating does not really go through the controls).

5.1.1.2 Step 2. Estimation of the performance of the initial system

At step 2, the calculation tool is used for the first time for calculating the performing parameters of the current design system.

A. Calculation of the energy heating demand

The energy demand of the case study has been calculated trough SEAS3 according to the data collected at step 1 for the sanitary hot water system and the space heating system.

The annual energy demand in the sanitary hot water system ($E_{HW\ Demand}$) is 637kWh. It has been calculated with SEAS3 from the number of dwelling inhabitants (2 people) and considering an average consumption of 50 L/person/day (assumption of SEAS3). The monthly average solar contribution is 64.5% of the $E_{HW\ Demand}$ (calculated with SEAS *solare*, complementary software to SEAS3) which

corresponds to 399kWh/y, based on climatic data. From these figures, the non-solar energy demand can be calculated; amount of energy that the boiler has to provide ($E_{HW\ Boi\ Non\text{-}solar}$) which corresponds to 238kWh/y (monthly accumulation).

The annual energy demand for space heating ($E_{SH\ Demand}$) is 18,085kWh (calculated with SEAS3) and takes into account the climate conditions and the energy losses from the building envelope and the user behaviour. For instance, from May to September, the space heating is off.

Table 15 summarizes the figures of the energy demand, the solar and non-solar energy demand for the current design of the sanitary hot water and the space heating systems.

Table 15. Energy demand, solar and non-solar energy demand (kWh/y) of the current design.

SANITARY HOT WATER SYSTEM			SPACE HEATING SYSTEM
$E_{HW\ Demand}$	$E_{Sol\ OUTPUT}$	$E_{HW\ Boi\ Non\text{-}sol}$	$E_{SH\ Demand}$
637	399	238	18,085

B. Calculation of the energy losses and NRE consumption

The energy losses of the system are the sum of the losses of the components of the system (Equation 7). The NRE consumption is the energy that needs to enter the boiler for covering both services independently: sanitary hot water and space heating.

<u>B.1 Compilation or calculation of the performance levels of every component or sub-system using EU product policies</u>

Sanitary hot water system components

Manufacturers declare that the boiler has an energy label A (for sanitary water heating) with a water heating energy efficiency of 74.4% according to Regulation 811/2013 (EC, 2013e) on the energy label of combination heaters. The water heating function of the boiler has a load profile M according to tapping patterns described in Regulation 814/2013 (EC, 2013c) for combination water heaters.

The solar devices (solar panels, solar storage tank and solar pump) are indirectly regulated in what is called a package by Regulation 811/2013 on the energy labelling of combination heaters, so that its influence is added (giving credits in % of solar contribution) to the water heater efficiency. However, the solar contribution used in this case study has not been calculated through this package concept but with SEAS *solare*, since this software does not only uses data on the solar panel, the storage tank and the solar pump, but also on climatic data of the specific location of the dwelling.

The storage tank has an energy label D (90W of standing losses) according to Regulation 812/2013 (EC, 2013b). The annual energy losses of the storage tank are calculated through SEAS3 based on the figure of the thermal dispersion declared by the manufacturer (2 W/K) and climate data.

The energy losses of the distribution are not regulated through EU product policies so that, they were assessed through SEAS3 based on data compiled from the installed technology (length of pipes and isolation material).

Taps and showers have a direct influence on the sanitary hot water energy demand. This product group is only regulated by EU Ecolabel and GPP criteria and lacks of neither Ecodesign nor Energy Labelling Directives' requirements. The taps and showers used in the dwelling correspond to average market products. Thus, it is assumed that no significant energy losses or savings occur using installed taps and showers.

Table 16. Performance of the components of the sanitary hot water system of the current design.

COMPONENTS/ SUB-SYSTEM	PERFORMANCE	SOURCE
1.Boiler	Water heating energy efficiency ($\eta_{Boi\ HW}$): (load profile M) 74.4%.	Compiled from manufacturer's product sheet according to energy label A (Regulation 811/2013)
2.Solar sub-system	Solar contribution: 64.5%	Calculated with SEAS3 (*solare*) (ENEA, 2017)
3.Storage tank	Standing losses: 90W	Calculated from the figure of the thermal dispersion declared by the manufacturer. The standing losses correspond to an energy label D (Regulation 812/2013).
	Total losses (L_{ST}): 823 kWh/y	Calculated with SEAS3 (monthly calculation according to climate data)
4.Distribution components	Losses ($L_{HW\ Dist}$): 1,018 kWh/y	Calculated with SEAS3
5.Taps & Showers	No energy losses, no savings on the $E_{HW\ Demand}$	Case study assumption

Space heating components

The boiler has a seasonal space heating energy efficiency of 92% (energy label A for space heating) according to the manufacturer.

The losses from the distribution of the water for space heating have been assessed by SEAS3 according to length and isolation of the tubes which connect the boiler and the underfloor heating.

The efficiency of the underfloor heating is 97%, default value given by SEAS3 for this type of space heating emitters. This efficiency has not been calculated with real data of the case study since there are not agreed calculation methods and for time constrains.

The temperature control of the case study is indirectly included in packages (of combination heaters and temperature control) of Regulation 811/2013. According to EC, 2014b, it is a control type V and contributes to 3% of the seasonal space heating efficiency of packages of space heaters and solar device. It is assumed that the same 3% is achieved as savings from the energy output of the boiler.

Table 17. Performance of the components of the space heating system of the current design.

COMPONENTS	PERFORMANCE	SOURCE
1.Boiler (the same boiler as for the sanitary hot water system)	Seasonal space heating energy efficiency ($\eta_{Boi\ SH}$): 92%	Compiled from manufacturer's product sheet. Energy label A (Regulation 811/2013)
6.Distribution components	Losses ($L_{SH\ Dist}$): 38 kWh/y	Calculated with SEAS3
7.Underfloor heating	η_{UFloor} = 97%	Efficiency taken from SEAS3 (efficiency set up by default)
8.Controls	Temperature control: Type V: 3% of savings (S_{Cont})	Assumption based in information included in energy labelling (EC, 2014b).

B.2 Calculation of the energy flows of the system

Figure 11 shows the energy flows from one component to the next. Energy inputs/outputs and losses of every component (Table 18 and Table 19) are calculated according to Equation 5 and Equation 6 in the opposite direction of the energy flows.

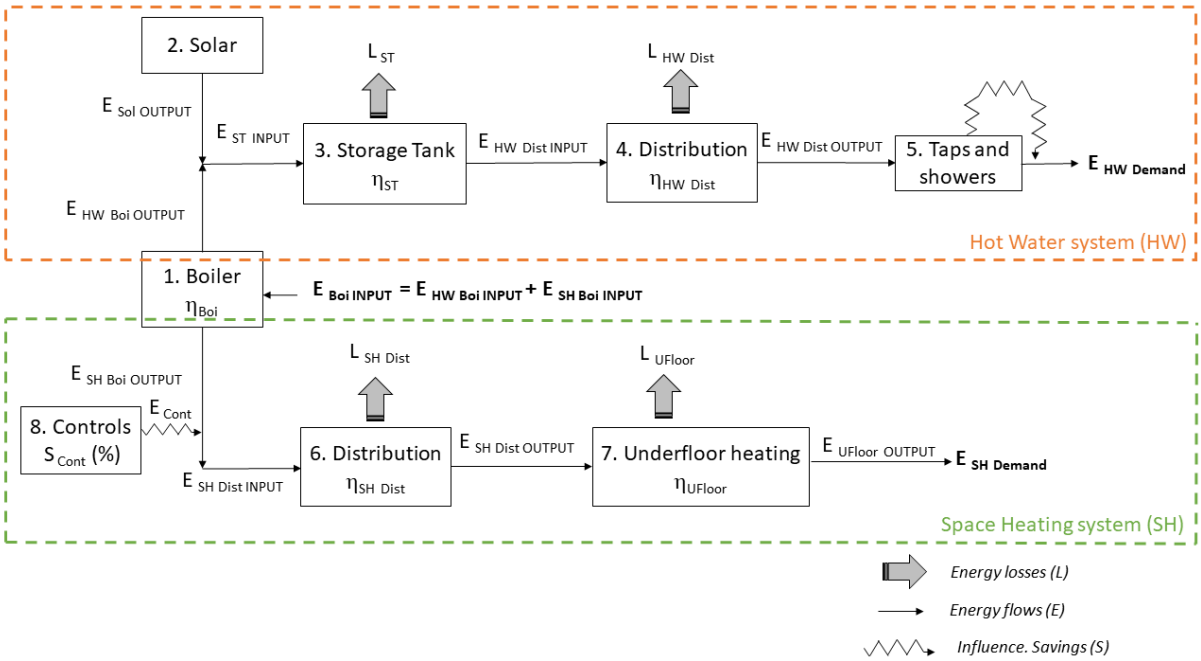


Figure 11. Energy flow chart of the heating systems of the case study.

In the sanitary hot water system, since no losses or savings are assumed in the installed taps and showers, in the current design $E_{HW\ Dist\ OUTPUT}$ = $E_{HW\ Demand}$ = 637 kWh/y. The energy provided by the boiler ($E_{HW\ Boi\ OUTPUT}$) is the substraction from the energy input in the storage tank ($E_{ST\ INPUT}$) of the energy output of the solar sub-system ($E_{Sol\ OUTPUT}$) (Equation 10). Then, the NRE consumption is the $E_{HW\ Boi\ INPUT}$ and it is calculated using Equation 5.

Equation 10:

$$E_{HW\ Boi\ OUTPUT} = E_{ST\ INPUT} - E_{Sol\ OUTPUT}$$

Table 18. Energy flows of the sanitary hot water system of the current design (kWh/y).

DISTRIBUTION COMPONENTS (HW)		STORAGE TANK		BOILER HW FUNCTION	
$L_{HW\ Dist}$ (Table 16)	$E_{HW\ Dist\ INPUT}$ (= $E_{ST\ OUTPUT}$)	L_{ST} (Table 16)	$E_{ST\ INPUT}$ (Equation 6)	$E_{HW\ Boi\ OUTPUT}$ (Equation 10)	$E_{HW\ Boi\ INPUT}$ (Equation 5)
1,018	1,655	823	2,478	2,079	2,795

In the space heating system, the energy demand is satisfied only through the boiler. Table 19 summarises the losses and energy flows of the space heating system.

Equation 11:

$$E_{SH\ Boi\ OUTPUT} = E_{Dist\ INPUT}/(1-S_{Cont})$$

Table 19. Energy flows of the space heating system of the current design (kWh/y).

UNDER FLOOR HEATING		DISTRIBUTION COMPONENTS SH		CONTROLS	BOILER SH FUNCTION	
L_{UFloor} (Equation 6)	$E_{UFloor\ INPUT}$ (Equation 5)	$L_{SH\ Dist}$ (Table 17)	$E_{SH\ Dist\ INPUT}$ (Equation 6)	E_{Cont} (Equation 5)	$E_{SH\ Boi\ OUTPUT}$ (Equation 11)	$E_{SH\ Boi\ INPUT}$ (Equation 5)
545	18,630	38	18,668	560	18,108	19,683

The importance of the energy losses of each component (Figure 12) aids at having an overview on how every component behaves within the overall system, regardless the type of energy used (natural gas or solar energy).

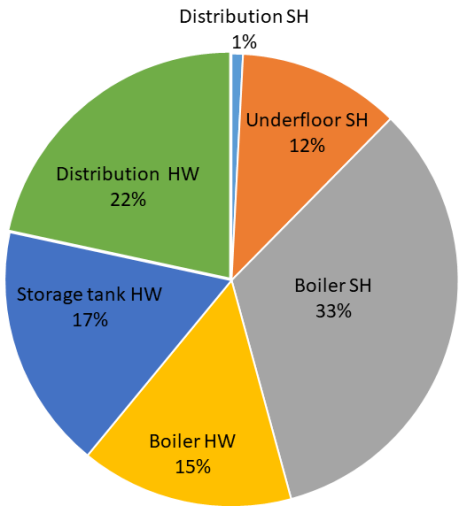


Figure 12. Contribution of each component to the overall energy losses of the heating systems of the current design.

The sum of the losses of the sanitary hot water and space heating systems, make the boiler the component with the highest losses (48%), despite its rather good performance (see Table 16 and Table 17). The distribution is the second with highest losses (22%). The storage tank represents 17% and the underfloor heating 12% of the total energy losses. In conclusion, according to results of Figure 12 the components to be upgraded would be, in order of relative importance: the boiler (joint water and space heating functions), the distribution components, the storage tank, and the underfloor heating.

C. Calculation of the low-emission energy efficiency

The energy efficiency of the heating systems of the case study is then defined as the ratio between the sanitary hot water or space heating demand ($E_{HW\ Demand}$ or $E_{SH\ Demand}$) of the dwelling and the energy input ($E_{HW\ Boi\ INPUT}$ or $E_{SH\ Boi\ INPUT}$) needed in the boiler:

Equation 12:

$$\eta_{WH\ SYSTEM} = E_{HW\ Demand}/E_{HW\ Boi\ INPUT}$$

Equation 13:

$$\eta_{SH\ SYSTEM} = E_{SH\ Demand}/E_{SH\ Boi\ INPUT}$$

Table 20. Energy performance parameters of the heating systems of the current design.

SANITARY HOT WATER SYSTEM			
$E_{HW\ Demand}$ (Table 15) (kWh/y)	$E_{HW\ Boi\ INPUT}$ (Table 18) (kWh/y)	$\eta_{HW\ SYSTEM}$ (Equation 12)	$L_{HW\ system}$ (Equation 7) (kWh/y)
637	2,795	22.8%	2,557
SPACE HEATING SYSTEM			
$E_{SH\ Demand}$ (Table 15) (kWh/y)	$E_{SH\ Boi\ INPUT}$ (Table 17) (kWh/y)	$\eta_{SH\ SYSTEM}$ (Equation 13)	$L_{SH\ system}$ (Equation 7) (kWh/y)
18,085	19,683	91.9%	2,158

The energy efficiency of the heating systems of the case study, according to the method proposed is 22.8% for the sanitary hot water system and 91.9% for the space heating system (Table 20). Looking at the figures of the energy efficiency and the total losses, the sanitary hot water system has a higher improvement potential than the space heating system. However, although the good performance of the space heating system versus the one of the sanitary hot water system, the energy demand of the former is much greater. Therefore, it might happen that improving the space heating system could bring higher energy savings in absolute values. Next section analyses the improvement potential of individual components of both systems in terms of systems savings (kWh/y).

5.1.1.3 *Step 3. Study of the influence of relevant individual components in the overall system*

In this step, the improvement potential of individual components is studied in terms of energy savings potential (kWh/y) on the overall system (in both sanitary hot water and space heating systems).

The gas boiler of the case study is regulated by Ecodesign and Energy labelling Directives under the product group “combination heaters” (Regulation 813/2013 and Regulation 811/2013, respectevely). The boiler is also regulated by EU Ecolabel and GPP under the product category “water-based heaters” (EC, 2014a; EC, 2016b). The gas boiler of the case study has an energy label A for both the water heating (74.4%) and the seasonal space heating functions (92%), the maximum class for boilers alone (Table 21 and Table 22). Higher classes can be achieved only at package level if solar devices are used jointly with the boiler. However, in this section results will be displayed per component; the boiler and the solar sub-system separately. Phased out energy classes and classes that can only be achieved with solar devices are not considered for this and further analysis.

Table 21. Performance levels of the water heating efficiency of the boiler.

Energy labelling (Regulation 811/2013)		Other product policies and assumptions
Energy efficiency class	Water heating energy efficiency (Profile M)	
A^{+++}	$\eta_{WH} \geq 163$	In theory, these energy classes can be only achieved in packages of boilers with solar devices (van Amerongen, 2015)
A^{++}	$130 \leq \eta_{WH} < 163$	
A^{+}	$100 \leq \eta_{WH} < 130$	
A	$65 \leq \eta_{WH} < 100$	74.4% Current design case study
B	$39 \leq \eta_{WH} < 65$	-
C	$36 \leq \eta_{WH} < 39$	Assumption: 38% to be average products in the market
D	$33 \leq \eta_{WH} < 36$	-
E	$30 \leq \eta_{WH} < 33$	30% - minimum ecodesign requirements (EC, 2013e)
F	$27 \leq \eta_{WH} < 30$	Phase out
G	$\eta_{WH} < 27$	Phase out

Table 22. Performance levels of the seasonal space heating efficiency of the boiler.

Energy Labelling (Regulation 811/2013)		Other product policies and assumptions
Energy efficiency class	Seasonal space heating energy efficiency	
A^{+++}	$\eta_{SH} \geq 150$	In theory, these energy classes can be only achieved in packages of boilers with solar devices and temperature control.
A^{++}	$125 \leq \eta_{SH} < 150$	
A^{+}	$98 \leq \eta_{SH} < 125$	
A	$90 \leq \eta_{SH} < 98$	98% EU Ecolabel (EC, 2014a) 92% Current design case study (benchmark) 90% GPP (EC, 2016b)
B	$82 \leq \eta_{SH} < 90$	86% - minimum Ecodesign requirements (EC, 2013d)
C	$75 \leq \eta_{SH} < 82$	Phased out
D	$36 \leq \eta_{SH} < 75$	Phased out
E	$34 \leq \eta_{SH} < 36$	Phased out
F	$30 \leq \eta_{SH} < 34$	Phased out
G	$\eta_{SH} < 30$	Phased out

Regarding the solar devices, three options have been assessed with SEAS *solare* (complementary software to SEAS3):

1. No solar devices: 0% solar contribution.
2. One solar panel (2,06 m^2): 65% solar contribution on the energy demand (as the initial system of the case study)
3. Two solar panels (4,12 m^2): 99.0% solar contribution on the energy demand.

The storage tank is included in the same product group of the same pieces of regulations than water heaters under the name “storage tank” regarding Ecodesign and Energy Labelling regulations (EC, 2013c and EC, 2013b, respectevely). Standing losses for each energy efficiency class (Table 23) are calculated with the storage volume (160L) according to the methodology set out in the Energy Labelling Regulation 812/2013 (EC, 2013b). Although energy classes B, A and A^+ are difficult to reach and unprobable to be used in a 60m^2 house, they are considered in Table 26 to show the maximum improvement potential of the storage tank.

Table 23. Performance levels of the storage tank.

Energy Labelling (Regulation 812/2013)		Other product policies and assumptions
Energy efficiency class	Standing losses (W)	
A^+	0 ≤ SL < 30	In theory, these energy classes can be only achieved with innovative insulation concepts such as evacuated systems or aerogel (Van Amerongen, 2015)
A	30 ≤ SL < 41	
B	41 ≤ SL < 57	
C	57 ≤ SL <80	Assumption: 69W are average products in the market (benchmark)
D	80 ≤ SL < 100	90W Current design case study
E	100 ≤ SL <130	Minimum ecodesign requirements in September 2017 (EC, 2013c)
F	130 ≤ SL <158	-
G	≥ 158	-

The temperature control and solar devices are not directly regulated under the corresponding product groups but as additions to the packages of space heaters with temperature control and solar device, through the Regulation 811/2013. Several control classes are defined for each type of temperature control (Table 24). As mentioned, the assessment of temperature controls in this case study assumes to have the same % in terms of savings on the energy output of the boiler.

Table 24. Performance levels of the temperature control.

Definition of temperature control classes (EC, 2014b)		Contribution to seasonal space heating energy efficiency of packages
Class I	On/off Room Thermostat	1%
Class II	Weather compensator control, for use with modulating heaters	2%
Class III	Weather compensator control, for use with on/off output heaters	1.5%
Class IV	TPI room thermostat, for use with on/off output heaters	2%
Class V	Modulating room thermostat, for use with modulating heaters	3% Case study Assumption: 3% are average products in the market (benchmark)
Class VI	Weather compensator and room sensor, for use with modulating heaters	4%
Class VII	Weather compensator and room sensor, for use with on/off output heaters	3.5%
Class VIII	Multi-sensor room temperature control, for use with modulating heaters	5%

Regarding taps and showers, although being regulated by EU Ecolabel and GPP criteria, these product policies do not provide a quantifiable measure of the energy consumption associated with these components. Instead, the Swedish Standard 820000:2010 (SIS, 2010) provides an energy classification for different levels of energy use for mechanical basin and mixing valves. I use the Swedish Standard 820000:2010 (SIS, 2010) to generate better and worse scenarios of the case study, modifying the energy demand (Table 25). It is assumed that taps and showers below the average products (current design) generate energy losses and taps and showers above average products generate energy savings on the energy demand.

Table 25. Performance levels of the taps and showers.

Swedish Standard 820000:2010 (SIS, 2010)		Case study assumption
Energy efficiency class	Measured energy use (kWh)	
A	≤ 1.6	53% savings
B	1.6 ≤ E < 2.2	35% savings
C	2.2 ≤ E < 2.8	18% savings
D	2.8 ≤ E < 3.4	Average products (no losses, no savings) Current design case study
E	3.4 ≤ E <4.0	18% losses
F	4.0 ≤ E <4.6	35% losses
G	< 4.6	53% losses

The distribution components of the sanitary hot water and space heating are not specifically regulated by any product policy. Distribution cannot feasibly be improved especially because the house is new or has been recently refurbished. In the sanitary hot water system, the design of the building and the location of the boiler (next to the radiant tubes and far away from the tapping points) hinder the possibility of using less tubing. On the other hand, the current isolation of the tubing is acceptable in terms of width (1.5 cm for the sanitary hot water system and 2.2 cm for the space heating system) and material (polyurethane). Thus, the distribution components for both the sanitary hot water and the space heating systems have a low feasibility for improvement and hence, they are not included in Table 26. In Table 26, the energy losses of the distribution are the ones of the current design ($L_{HW\ Dist}$ =1,018 kWh/y for the sanitary hot water system and $L_{SH\ Dist}$ = 38kWh/y for the space heating system).

Similarly, the underfloor heating recently installed in the dwelling of the case study makes not feasible its improvement. This type of component which delivers space heating is not regulated by any product policy and the accounting of its losses has not been yet agreed. These facts make the underfloor heating difficult to be modified so it is consider as not relevant and hence, not included in Table 26. In Table 26, the efficiency of the underfloor heating is the one of the current design (η_{UFloor} = 97%).

Table 26. Data on the improvement potential analysis of individual components of the current design.

VARIABLES (Component/ sub-system)	CURRENT DESIGN	PERFORMANCE LEVELS	SOURCE/COMMENTS
SANITARY HOT WATER SYSTEM			
Solar panels (number of panels)	1 (2.06 m^2)	0, 1, 2 solar panels	Same characteristics of the one already installed.
Boiler (energy class/water heating energy efficiency)	A (74.4%)	E (30-33%), D (33-36%), C (36-39%), B (39-65%), A (65-100%)	Energy labelling (Regulation 811/2013), Ecodesign (Regulation 813/2013) and EU Ecolabel (EC, 2014a). See Table 21.
Storage tank (energy class/ standing losses)	G (90W)	G (>158W), F (158-130W), E (130-100W), D (100-80W), C (80-57W), B (57-41W), A (41-30W), A+ (<30W)	Energy labelling (Regulation 812/2013) and minimum Ecodesign requirements (Regulation 814/2013). See Table 23.
Taps and showers (energy losses/savings on energy demand)	0% losses 0% savings	-53%, -35 and -18% losses 18%, 35%, 53% savings	Assumption based on Swedish label SS 820000:2010 (SIS, 2010). See Table 25.
SPACE HEATING SYSTEM			
Boiler (energy class/ seasonal space heating energy efficiency)	A ($\eta_{SH\ Boi}$ 92%)	B (82-89%), A (90-96%)	Energy labelling (Regulation 811/2013) and Ecodesign (Regulation 813/2013) and EU Ecolabel (EC, 2014a). See Table 22.
Controls	Type V: 3% savings	No controls (0% savings), class II (2% savings), class VI (4% savings), class VIII (5% savings)	Assumption made based on Energy labelling (Regulation 811/2013). See Table 24. (Only classes affecting modulating heaters)

Figure 13 has been built based on every performance level of each individual component (third column of Table 26). The performance level is modified one at a time and the rest of the components performance levels are left as in the current design. Thus, Figure 13 shows results of 38 heating systems (including the initial system): 26 (3 solar panels + 7 boilers + 9 storage tanks + 7 taps and showers) sanitary hot water systems and 9 (4 boilers + 5 controls) space heating systems.

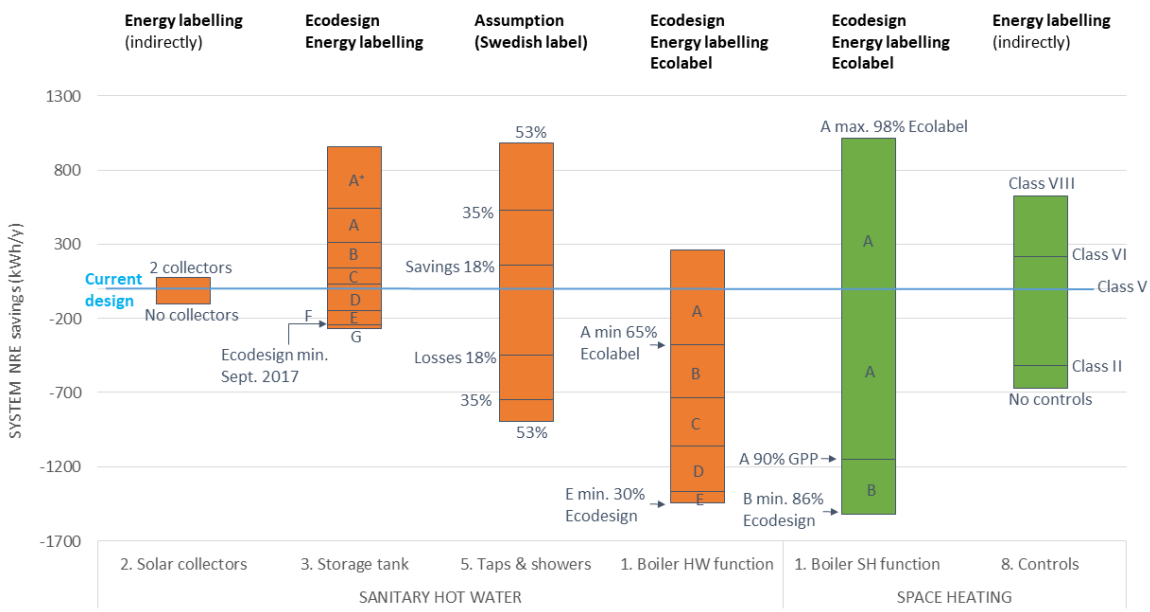


Figure 13. Results of the improvement potential analysis of individual relevant components.

Results of Figure 13 show, for each component, the system potential for improvement expressed in energy savings (kWh/y). Improvement would be negative if for example, the current boiler (labelled A) were replaced by a worse technology (energy classes from B to E). Therefore, upgrading the space heating function of the boiler could bring the highest energy savings to the sanitary hot water system (up to 1,012 kWh/y). Efficient taps and showers could lead to savings of 981 kWh/y in the sanitary hot water system. An upgrade of the storage tank up to the maximum energy class (A^+) could lead to energy savings of 960 kWh/y in the system. Using temperature controls of class VIII could lead to savings of 626 kWh/y in the space heating system. The sanitary hot water function of the boiler (259 kWh/y savings) and the solar panels (78 kWh/y savings) have less significant potential for improvement.

Note that the relationship of some of the performance levels of certain components (i.e. boiler and storage tank) and the energy efficiency of the system is not linear (Figure 13). This happens because higher energy classes are more difficult to reach.

It can be concluded that the most influent components (which would achieve the highest savings) are the space heating function of the boiler, the taps and showers and the storage tank.

5.1.1.4 Summary of outputs of phase 1

At the end of phase 1, the designer has an overview on how the initial system is behaving with regard system aspects (location, building characteristics, etc.) and how the components are affecting the overall system. In particular:

- The global context is defined (north Italy, 60m^2, etc.) and the heating systems are modelled (the solar sanitary hot water system and the space heating system) (Step 1, section 5.1.1.1).
- Through the calculation tool, the heating demand is estimated with a building simulation tool SEAS3 (637 kWh/y for hot water and 18,085 kWh/y for space heating) (Step 2, section 5.1.1.2 A).
- Through the calculation tool, the energy losses (2,557 kWh/y for the hot water system and 2,158 kWh/y for the space heating system), NRE consumption (2,795 kWh/y for the hot water system and 19,683 kWh/y for the space heating system) and the efficiency (22.8% for the hot water system and 91.9% for the space heating system) of the initial system are calculated (Step 2, section 5.1.1.2 B).
- Relevant components are identified (solar panels, boiler, storage tank, taps and showers and temperature control) as well as their performance levels based in EU product policy data (Step 3, section 5.1.1.3).
- The contribution of components to system savings is assessed and components with highest improvement potential are identified (boiler, storage tank, taps and showers and temperature controls) (Step 3, section 5.1.1.2).

5.1.2 Phase 2. Improvement: investigation of a better performing system

This section aims at searching improved solutions with regard the initial system.

It is assumed that the components used in the following alternatives are fulfilling the same function as the initial heating system and that these are located in the same place. Thus, only the performance levels of the components are modified. New components and/or technology could be added only if the system modelling made at step 1 of the method would it would be revised and still valid. If it is not valid, the “new” system would have to be modelled again.

5.1.2.1 Step 4. Analysis of the best, benchmark and worst systems

The worst case is set according to information of minimum Ecodesign requirements and/or lowest energy class. The benchmark are considered average products in the market. The best case is set through feasible EU Ecolabel or GPP performances or the highest energy classes.

The number of solar panels is considered constant (equal to 1 solar panel, 2.04 m^2 solar surface) since their improvement potential is very low in this case study (Figure 13). Then, the number of solar panels, the distribution and the underfloor heating are considered the same as the current design and their best or worst options are not studied.

Table 27 shows the details of the best and worst scenarios proposed for the sanitary hot water and the space heating systems.

Table 27. Worst, benchmark and best combinations of components' performance levels.

Component	WORST	BENCHMARK (average products in the market)	CURRENT DESIGN	BEST
SANITARY HOT WATER SYSTEM				
Boiler label class (water heating energy efficiency)	E (30%)	C (38%)	A (74%)	A (100%)
Number of solar panels (solar contribution)	1 panel (64.5%)	1 panel (64.5%)	1 panel (64.5%)	1 panel (64.5%)
Storage tank label class (standing losses)	G (158W)	C (69W)	D (90W)	C max. (57W)
Distribution losses	1,1018 kWh/y	1,1018 kWh/y	1,1018 kWh/y	1,1018 kWh/y
Taps and showers label (savings/losses on the energy demand)	G 53% losses	D 0% savings/losses	D 0% savings/losses	A 53% savings
SPACE HEATING SYSTEM				
Boiler label class (space heating energy efficiency)	B (86%)	A (92%)	A (92%)	A (97%)
Temperature controls class (savings)	No controls	Class V (3%)	Class V (3%)	Class VII (5%)

Results obtained from the calculation tool deliver the figures of the performing parameters of the best, benchmark and worst alternatives (Table 28). Note that the best alternative assumes a low energy demand thanks to efficient taps and showers and that the worst one considers high energy demand due also to inefficient taps and showers.

Table 28. Energy performance parameters for the worst, benchmark and best combinations of the sanitary hot water system.

	NRE consumption (kWh/y)	Energy losses (kWh/y)	Energy demand (kWh/y)	Low-emission energy efficiency
WORST	9,538	9,140	975	10.2%
BENCHMARK	5,018	4,780	637	12.7%
CURRENT DESIGN	2,795	2,557	637	22.8%
BEST	878	1,541	299	45.8%

Figure 14 shows how the energy efficiency of the current design of the sanitary hot water system is better than the benchmark and that the improvement potential up to the best case is 23%.

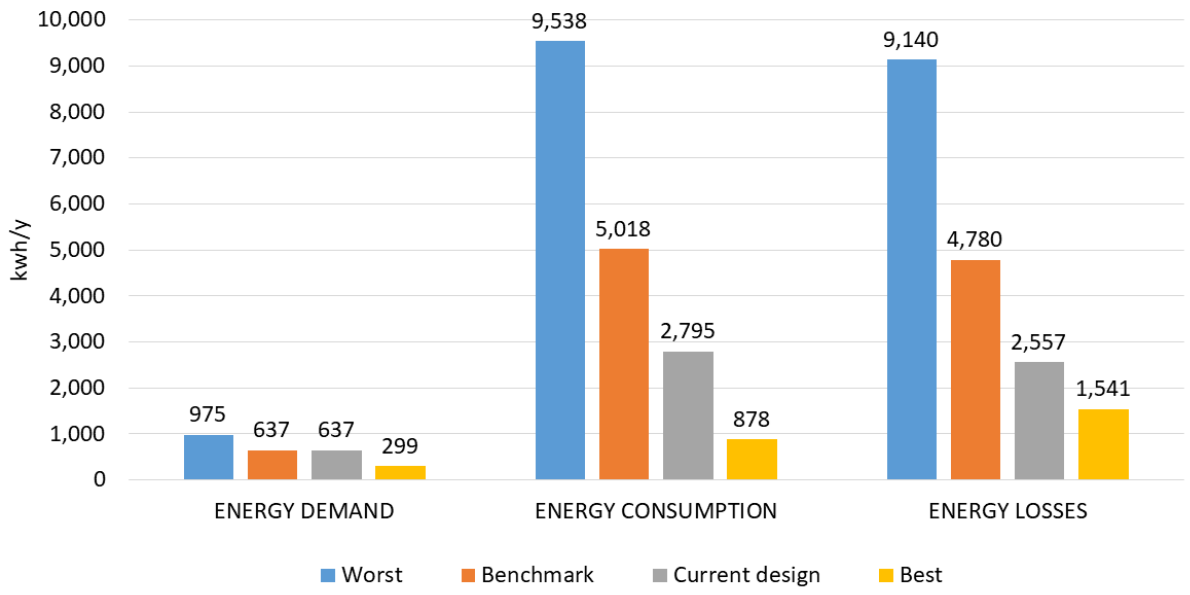


Figure 14. Energy demand, consumption and losses of the worst, benchmark and best combinations of the sanitary hot water system.

Regarding the space heating system, the current design is the benchmark system and the improvement potential up to the best alternative proposed is only near 5%.

Table 29. Energy performance parameters for the worst, benchmark and best combinations of the space heating system.

	NRE consumption (kWh/y)	Energy losses (kWh/y)	Energy demand (kWh/y)	Low-emission energy efficiency
WORST	21,707	3,622	18,085	83.3%
CURRENT DESIGN/ BENCHMARK	19,682	2,158	18,085	91.9%
BEST	18,096	945	18,085	97.0%

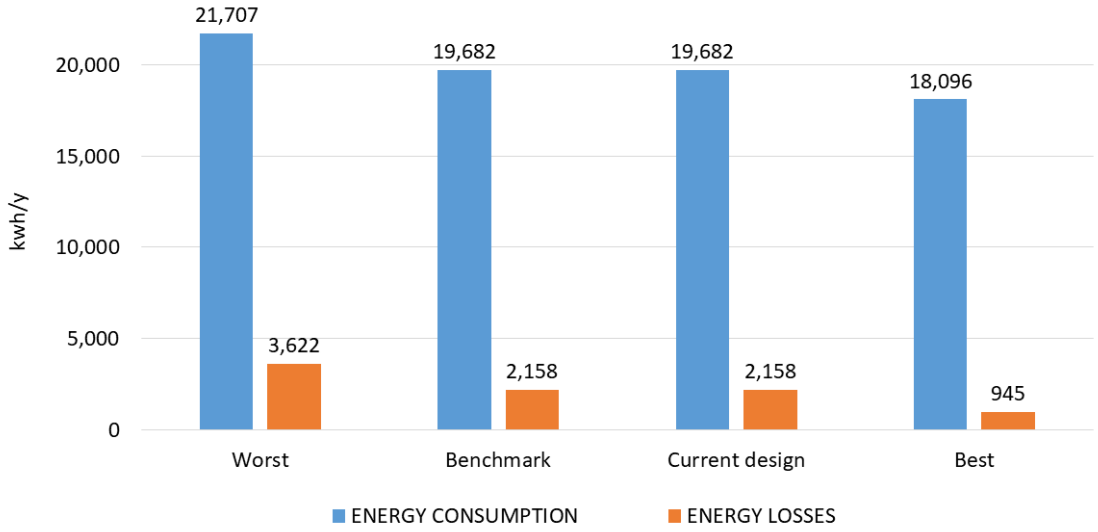


Figure 15. Energy consumption and losses of the best, benchmark and worst combinations of the space heating system.

Even if the improvement potential up to the best alternative is only 5% in absolute terms the value is not negligible, being equal to 1,587 kWh/y. It is slightly lower than the potential savings from the hot water system, evaluated in 2,141 kWh/y. The sum of the two contributions could bring a reduction of the NRE consumption equal to 28%.

5.1.2.2 Step 5. Analysis of other alternatives

Sanitary hot water system

For the sanitary hot water system, it is analysed how the combination of different performance levels of the components affects the NRE consumed by the boiler. Assumptions have been made to generate design options:

- As the number of solar panels has poor potential for improvement (Figure 13), only one panel is considered in the following;
- The water heating energy efficiency of the boiler could be improved up to 100%. Two A-labelled boilers are considered (74% and 100%);
- The storage tank could be easily improved up to the minimum value of energy class B (57W), since this class represents the average products in the market (Van Amerongen, 2015). Four energy classes are considered: D (current design), D min., C and B;
- Regarding taps and showers, four levels have been considered (0%, 18%, 35% and 53% of savings on the $E_{HW\ Demand}$).

Given these assumptions, there are 32 possible sanitary hot water system design options (1 solar panel x 2 boiler water heating x 4 storage tank x 4 taps and showers). Each quartet of bars represents a combination of a boiler (74% and 100% of water heating energy efficiency) and a storage tank (from D to B energy class).

The colour of each bar corresponds to the four different levels of efficiency of the taps and showers considered: D class of the current design in blue (0% savings on the energy demand), D minimum in orange (18% savings), B class in grey (35% savings) and A class in yellow (53% savings).

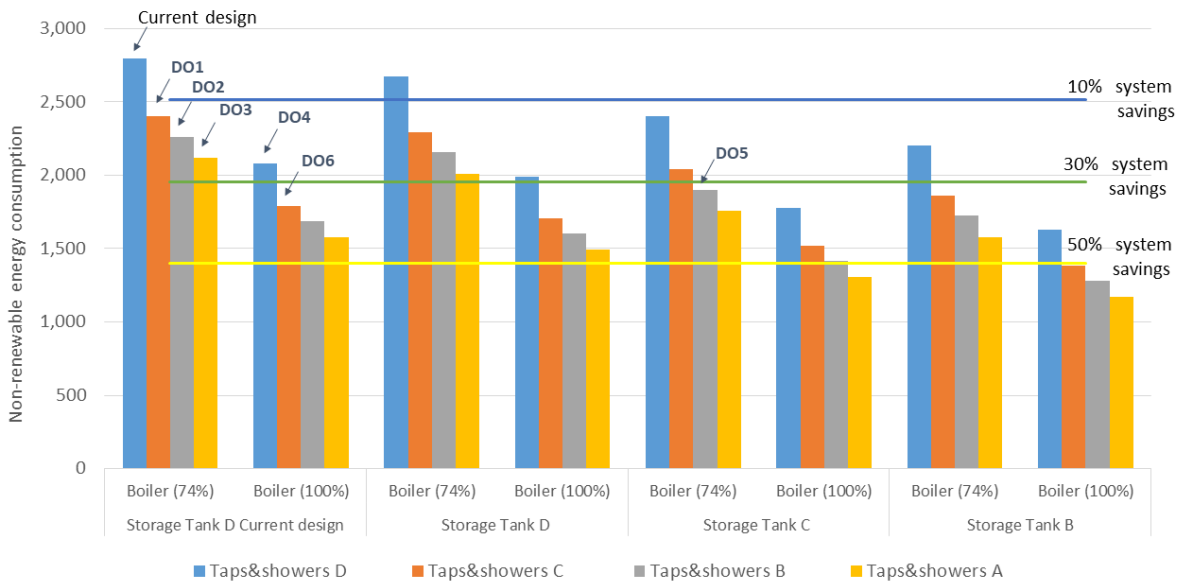


Figure 16. Alternative solutions based on combining products with different performance levels in the sanitary hot water system.

According to Figure 16, for certain energy-savings system target (with respect to the current design) the designer could choose among various design options (DOs) or combinations of products with different performance levels. The easiest six design options have been chosen through modifying the minimum number (one or two) of components. For instance, achieving a system's energy saving of at least 10% to 30%, the taps and showers need to be replaced by ones with a C class (DO1). Other options include choosing even more efficient taps and showers (DO2 and DO3) or replacing the boiler by one with 100% of water heating energy efficiency (DO4). To achieve system savings of at least 30% to 50%, the storage tank would have to be upgraded to C energy class and replace the taps and showers by others with an energy class B (DO5). Another option could be to use a boiler with 100% of water heating energy efficiency, and taps and showers must be replaced by others with a C energy class (DO6). Table 30 summarises such design options.

Table 30. Summary of design options of the sanitary hot water system

COMPONENTS	Current Design	DO1	DO2	DO3	DO4	DO5	DO6
Boiler label class(water heating energy efficiency)	A (74.4%)	A (74.4%)	A (74.4%)	A (74.4%)	**A (100%)**	A (74.4%)	**A (100%)**
Number of solar panels (solar contribution)	1 panel (64.5%)	1 panel (64.5%)	1 panel (64.5%)	1 panel (64.5%)	1 panel (64.5%)	1 panel (64.5%)	1 panel (64.5%)
Storage tank label (Standing losses)	D (90W)	D (90W)	D (90W)	D (90W)	D (90W)	**C (57W)**	D (90W)
Distribution losses	1,1018 kWh/y	1,1018 kWh/y	1,1018 kWh/y	1,1018 kWh/y	1,1018 kWh/y	1,1018 kWh/y	1,1018 kWh/y
Taps and showers label (saving on energy demand)	D 0% savings	**C 18% savings**	**B 35% savings**	**A 53% savings**	D 0% savings	**B 35% savings**	**C 18% savings**

In addition, Table 31 shows the results of the performing parameters of the six selected solutions.

Table 31. Energy performance parameters of the design options of the sanitary hot water system

ALTERNATIVES OF IMPROVEMENT	NRE consumption (kWh/y)	Energy losses (kWh/y)	Energy demand (kWh/y)	Energy efficiency (%)	Savings (kWh/y and %)
DO1	2,402	2,456	522	21.7	393 (14.0%)
DO2	2,264	2,421	414	18.3	531 (19%)
DO3	2,118	2,384	299	14.1	677 (24.2%)
DO4	2,079	1,841	637	30.6	715 (25.6.4%)
DO5	1,902	2,027	414	21.8	892 (31.9%)
DO6	1,787	1841	522	29.2	1008 (36.0%)

Space heating system

In the case of the space heating system, only the combination of the performance levels of the boilers and the controls is analysed since they are the relevant components which have potential for improvement.

- The space heating energy efficiency of the boiler could be improved up to 98%. We consider two A-labelled boilers, but with different space heating energy efficiencies: 92% and 98%;
- Regarding the controls, 3 options are considered; class V (3% savings, current design), class VI (4% savings) and class VIII (5% savings).

The rest of components (distribution of the space heating and underfloor heating) are kept with the same values as in the current design (see Table 17). Therefore, there are 6 possible combinations (2 x 3). Figure 17 shows the NRE consumption for each combination.

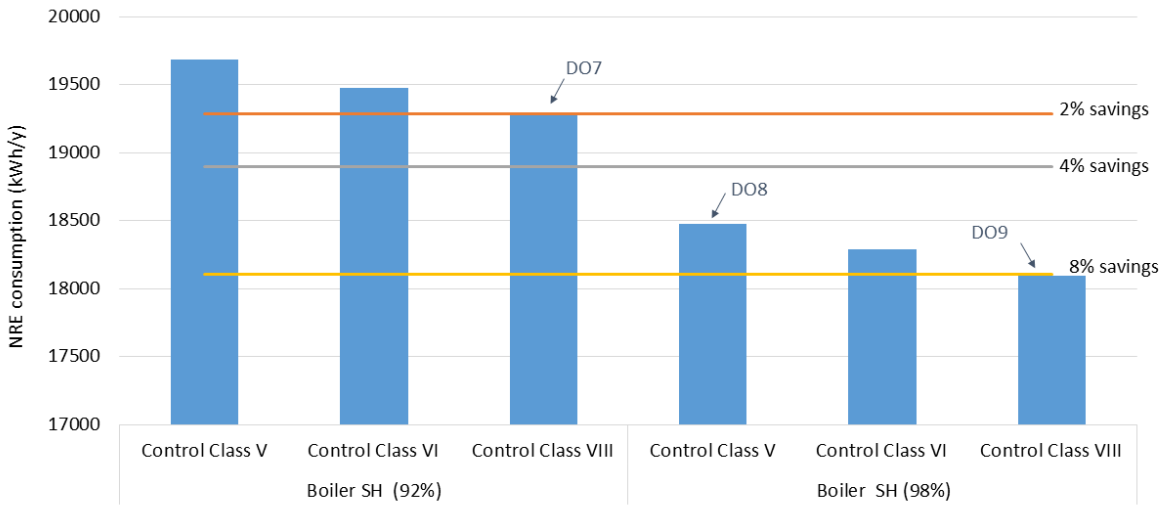


Figure 17. Alternatives solutions from the combination of different components performance levels in the space heating system.

Saving targets are set up at 2%, 4% and 8% and 3 solutions from Figure 17 (Table 32) are chosen for a more detailed analysis shown in Table 32 and Table 33.

Table 32. Summary of design options of the space heating system

COMPONENTS	Current design	DO7	DO8	DO9
Boiler label class(space heating energy efficiency)	A (92%)	A (92%)	**A (92%)**	**A (97%)**
Distribution losses	38 kWh/y	38 kWh/y	38 kWh/y	38 kWh/y
Underfloor heating efficiency	97%	97%	97%	97%
Temperature control class(savings)	Class V (3%)	**Class VIII (5%)**	Class V (3%)	**Class VI (4%)**

Table 33. Energy performance parameters of the design options of the space heating system.

ALTERNATIVES OF IMPROVEMENT modifying:	NRE consumption (kWh/y)	Energy losses (kWh/y)	Energy demand (kWh/y)	Energy efficiency (%)	Savings (kWh/y and %)
DO7	19,277	2,135	18,085	93.8%	406 (2.1%)
DO8	18,477	953	18,085	97.9%	1205 (6.1%)
DO9	18,096	945	18,085	99.9%	1,586 (8.1%)

In conclusion, three main results can be drawn from the case study. Firstly, the influence of the performance levels of individual components (Figure 13) on the system can be studied with the proposed method. A second result is that proposing a feasible benchmark for the products' performance levels (Figure 14, and Figure 15), it can be quantified if the current design of the case study is above or below the benchmark system. The third type of results helps designers to study and compare various design alternatives (system configurations) combining different component performance levels and simulating their system performance (Figure 16 and Figure 17). It is then possible to reach a certain energy efficiency target through combining different performance levels of the installed devices. This could be done either through simple modifications to the current devices or through the substitution by a better device.

5.1.3 Economic analysis of design alternatives

An additional economic analysis has been carried out in the case study to illustrate how results concerning energy savings of the design options presented in the previous section 5.1.2.2 can be combined with other design criteria.

The life cycle costs have been calculated by adding the investment costs to the present values of the operation costs during a 20-year lifetime as proposed by Zambrana- Vasquez et al. (2015). The investment costs were the ones of the real product purchases and their installation of all the sanitary hot water and space heating systems' equipment in 2012. The discount rate considered is 2.4%. It has been calculated with the inflation and interest rates, according to the analysis of the evolution of prices in previous years in Italy (based on Eurostat). The cost of the natural gas is 0.0776€/kWh with an annual growth rate of 4%, according to the analysis of the gas prices for domestic consumers of previous years in Italy (Eurostat, 2016). The water price is the current one in Lombardy (1.287 €/m^3) with an annual growth rate of 2.5% (EC-JRC, 2014). All costs exclude VAT. The purchase costs of the better boiler and storage tanks are based on real prices of the current Italian market.

For the improved taps and showers, Table 34 shows the assumptions made according to the installation of aerators and flow regulators (EC and AEA, 2011) to the current taps and showers. The prices of these technologies and their substitution rate are European averages (EC-JRC, 2014) and they have been included in the operation costs.

Table 34. Assumptions of improved taps and showers for the economic analysis

	0% savings – class D	18% savings - class C	35% savings - class B	53% savings - class A
Kitchen tap	Current	Current	Aerator + flow regulator	Aerator + flow regulator
Bathroom basin tap	Current	Aerator + flow regulator	Aerator + flow regulator	Aerator + flow regulator
Bathroom shower	Current	Current	Current	Aerator + flow regulator

Results of the economic analysis of the sanitary hot water system are shown in Table 35. DO3 and DO5 achieve the highest cost savings (15% and 14,6% respectively) with respect the current design. From an economic point of view, between these two options, DO3 is preferable since only one product is modified and thus it is easier to implement. However, DO5 achieve more energy savings. DO2, DO6 and DO1 achieve similar cost savings (10.1%, 8.8% and 7.1%,respectively). DO1 and DO2 are easier to implement since only taps and showers are modified, but DO6 achieve higher energy savings. DO4 achieves the least cost savings mainly because the high cost of the replacement of the boiler is not counterbalanced by the energy savings due to its improvement.

In conclusion, water costs savings due to the improved taps and showers are crucial, since the installation of aerators and flow regulators and its maintenance are much cheaper than the replacement of the boiler or the storage tank. In addition, the water savings are quite high (18%, 35% and 53%) depending on the taps and showers energy class. While the improved taps and showers represent water and energy savings, the replacement of the boiler and the storage tank achieve only energy savings. Therefore, designers should find a compromised solution between the energy and cost savings.

Table 35. Economic results of design options of the sanitary hot water system (€)

	Current Design	DO1	DO2	DO3	DO4	DO5	DO6
Product costs	5,190	5,190	5,190	5,190	6,592	5,290	6,592
Installation costs	800	800	800	800	1000	1000	1000
Investment costs (products and installation)	**5990**	**5990**	**5990**	**5990**	**7592**	**6290**	**7592**
Natural gas costs for water heating	10,797	9,582	9,156	8,398	8,584	8,037	7,682
Water costs	1,388	1,188	999	800	1,388	999	1,188
Repair & maintenance	100	209	279	349	100	279	209
Operation costs (natural gas + water + repair & maintenance)	**12,285**	**10,979**	**10,434**	**9,546**	**10,072**	**9,315**	**9,079**
TOTAL	**18,275**	**16,969**	**16,424**	**15,536**	**17,664**	**15,605**	**16,671**
Cost savings with respect the current design (€)		1,306	1,851	2,739	610	2,670	1,604

Regarding the space heating system, economic results are shown in Table 36. DO7, DO8 and DO9 achieve 1.5%, 3.1% and 4.4% of cost savings. These percentages are lower than in the sanitary hot water system with respect the current design, however, absolute values in € are similar. The replacement of the boiler in the space heating system is more expensive than the replacement of the temperature control but the energy savings are much higher when replacing the boiler by a better one.

Table 36. Economic results of design options of the space heating system (€)

	Current Design	DO7	DO8	DO9
Product costs	4,732	4,952	6,135	6,355
Installation costs	825	850	1,025	1,050
Investment costs (products and installation)	**5,557**	**5,802**	**7,160**	**7,405**
Natural gas costs for water heating	62,985	61,731	59,258	58,081
Repair & maintenance	200	200	200	200
Operation costs (natural gas + water + maintenance and repair)	**63,185**	**61,931**	**59,458**	**58,281**
TOTAL	**68,742**	**67,733**	**66,618**	**65,686**
Cost savings with respect the current design (€)		1,010	2,124	3,057

It should be noted that replacing the boiler of the current design would most probably imply to improve both water heating and space heating efficiencies (not only one

function of the boiler). Then results of Table 35 and Table 36 could be combined. However, this synergy has not been taken into account in this research.

These results show that the set of indicators on energy performance calculated through the method proposed can be advantageously combined with economic indicators to support informed decision-making by designers.

5.2 Extended analysis of the case study

The method proposed (section 4) generates the initial model at Step 1 and this is supposed to be fixed throughout the next steps. In this section the geographical conditions in the case study and the initial model are modified.

This section aims to prove that the method proposed works not only for the specific case study of previous section 5.1 but also with different heating system models.

This section consists in analysing certain changing conditions in the case study, which are not considered to be modified, in principle, in the main method. Results of this section will show if the method is still valid when some aspects are modified in the original model:

- The change of location from the north to the south of Italy could show for instance if the solar collectors have more influence in the heating systems and if the space heating is still behaving correctly with a significant less energy demand.
- Enlarging the demand by doubling the number of people living in the dwelling could show the better or worse behaviour of the boiler on satisfying higher energy demands.
- Changing the technology of the main generator could improve or degenerate the efficiencies of each heating system.

For each of these assumed cases, Phase 1 of the method will be applied again, to show how systems (and its components) behaviour change when parameters such as climate, energy demand or technology are modified. Only relevant modifications on the results will be shown in the next sections (blue font on the tables). Phase 2 will be not run in the next extended analysis of the case study since it is assumed to be applicable once phase 1 has been carried out.

5.2.1 Change of location: from north to south Italy

Step 1 (Figure 9 and Figure 10) of the method is not changing when the same systems are used in the south (Palermo) instead of the north (Ispra) Italy.

5.2.1.1 Step 2. Estimation of the performance of the initial system

In the sanitary hot water system, the energy demand does not change since the number of people living in the dwelling is not modified. In contrast, when the location is changed, the climate conditions are different and thus, the solar contribution of the solar sub-system is higher in the south (77.2%) than in north (64.5%) Italy. Losses from the storage tank (711 instead of 823 kWh/y) are also reduced due to the lower

difference of temperatures between the external environment and the water. SEAS3 was used again to assess the solar contribution and the losses from the storage tank and the distribution.

Regarding the space heating system, the energy demand (calculated with SEAS3 software) in the south of Italy is significantly lower than in the north. The rest of parameters remain the same.

It is assumed that the distribution losses nor in the sanitary hot water system neither in the space heating system do not change since SEAS3 software does not consider the distribution to be modified in neither of the systems in south Italy. This is probably due to the fact that the distribution losses are calculated in SEAS3 based only in characteristics of the tubes (length, type and width of isolation, depth of underground of the tubes, etc.) and not based in the external air temperature. Then, here it is also assumed that the distribution losses do not change.

Table 37 shows in blue the parameters which have changed with respect the north Italy (Ispra) (Table 15).

Table 37. Energy demand, solar and non-solar energy demand of the case study in south Italy (kWh/y)

SANITARY HOT WATER SYSTEM			SPACE HEATING SYSTEM
$E_{HW\ Demand}$	$E_{Sol\ OUTPUT}$	$E_{HW\ Boi\ Non\text{-}sol}$	$E_{SH\ Demand}$
637	490	147	5,560

Table 38 and Table 39 show the figures of the energy flows for the hot sanitary and space heating systems, respectively in south Italy. Calculations of the energy flows have been assessed with the Excel tool created for this purpose (see section 5.1.1) and modifying the solar contribution, storage tank losses and space heating energy demand for Palermo (previously assessed with SEAS3).

Table 38. Energy flows of the sanitary hot water system of case study in south Italy (kWh/y)

DISTRIBUTION COMPONENTS (HW)		STORAGE TANK		BOILER HW FUNCTION	
$L_{HW\ Dist}$ (Table 16)	$E_{HW\ Dist\ INPUT}$ (= $E_{ST\ OUTPUT}$)	L_{ST} (Table 16)	$E_{ST\ INPUT}$ (Equation 6)	$E_{HW\ Boi\ OUTPUT}$ (Equation 10)	$E_{HW\ Boi\ INPUT}$ (Equation 5)
1,018	1,655	711	2,366	1,876	2,522

The NRE consumption in the sanitary hot water system (2,522 kWh/y) is slighter lower in the south than in north Italy (2,795kWh/y, see Table 18) due to the higher solar contribution and lower losses in the storage tank.

Table 39. Energy flows of the space heating system of the case study in south Italy (kWh/y)

UNDER FLOOR HEATING		DISTRIBUTION COMPONENTS SH		CONTROLS	BOILER SH FUNCTION	
L_{UFloor} (Equation 6)	$E_{UFloor\ INPUT}$ (Equation 5)	$L_{SH\ Dist}$ (Table 17)	$E_{SH\ Dist\ INPUT}$ (Equation 6)	E_{Cont} (Equation 5)	$E_{SH\ Boi\ OUTPUT}$ (Equation 11)	$E_{SH\ Boi\ INPUT}$ (Equation 5)
172	5,733	38	5,771	173	5,598	6,084

Regarding the space heating system, the NRE consumption (calculated with the Excel tool) is significantly lower in south than in north Italy (19,683 kWh/y, see Table 19) due to the lower space heating energy demand.

Figure 18 shows the relative importance of the energy losses of each component for both sanitary hot water and space heating systems in south Italy. The boiler (joint HW and SH functions) is still the component with higher losses (37%). The distribution losses are the second with the highest losses (33%). The storage tank represents 23% and the underfloor heating 6% of the total energy losses. Therefore, the order of the components to be upgraded would remain the same as in the case of north Italy (Figure 12).

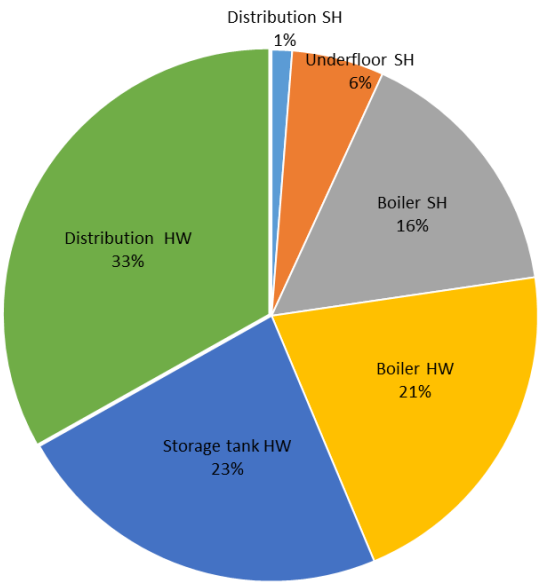


Figure 18. Contribution of each component to the overall energy losses of the case study in south Italy.

Table 40 shows the energy performance parameters of the case study for south Italy. The low-emission energy efficiency of the hot water system is slighter higher than that for north Italy (22.8%, see Table 20) since more renewable energy is used. In the case of the space heating system, the low-emission energy efficiency is lower than for north Italy (91.9%, see Table 20). This is due to the worse use of the capacity of the boiler. The sanitary hot water system has a higher improvement potential than the space heating system, looking at the figures of the low-emission energy efficiency and the total losses. However, in absolute values, the energy demand is still much higher in the space heating system.

Table 40. Energy performance parameters of the heating systems of the case study in south Italy (Palermo)

SANITARY HOT WATER SYSTEM			
$E_{HW\ Demand}$ (Table 15) (kWh/y)	$E_{HW\ Boi\ INPUT}$ (Table 18) (kWh/y)	$\eta_{HW\ SYSTEM}$ (Equation 9)	$L_{HW\ system}$ (Equation 7) (kWh/y)
637	2,522	25.3%	2,375
SPACE HEATING SYSTEM			
$E_{SH\ Demand}$ (Table 15) (kWh/y)	$E_{SH\ Boi\ INPUT}$ (Table 17) (kWh/y)	$\eta_{SH\ SYSTEM}$ (Equation 9)	$L_{SH\ system}$ (Equation 7) (kWh/y)
5,561	6,084	91.4%	697

5.2.1.2 Step 3. Study of the influence of relevant individual components in the overall system

This study is carried out under the same principles and assumptions than in section 5.1.1.3.

Figure 19 shows the influence of individual components on the energy savings of both systems in south Italy.

The use of efficient taps and showers could lead to the highest savings (up to 912 kWh/y). The second component that allows better savings if it is improved is the storage tank (901 kWh/y). Upgrading the space heating function of the boiler up to the maximum, brings 343 kWh/y of savings while upgrading the sanitary hot water function brings 263 kWh/y. Better controls could lead to 156 kWh/y of savings. The solar panels have the least potential for improvement (52 kWh/y).

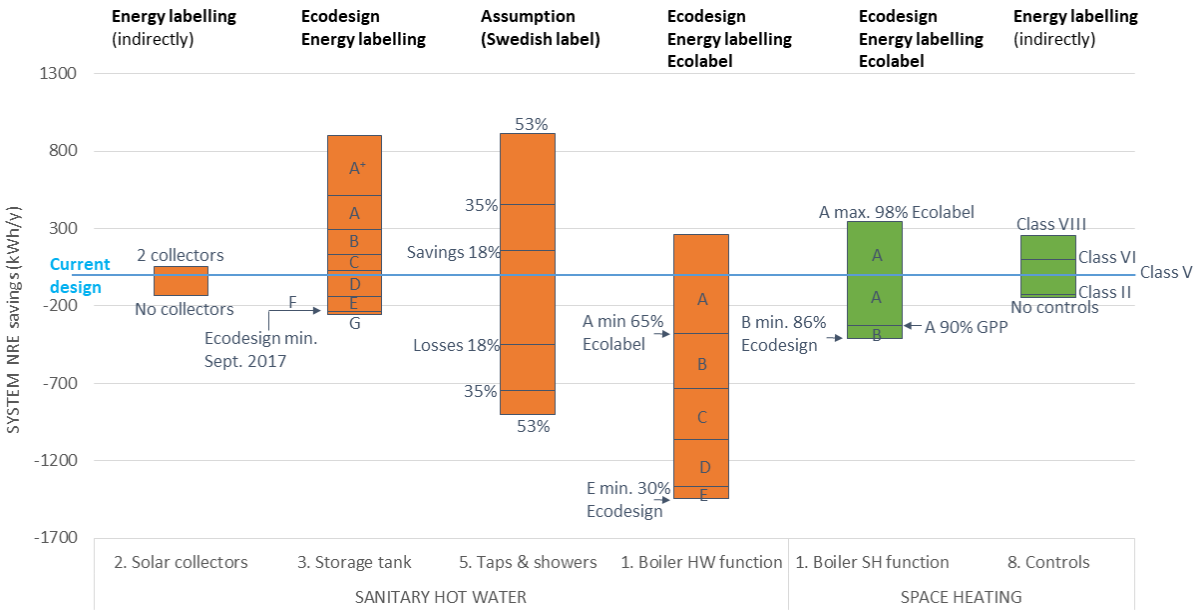


Figure 19. Results of the improvement potential analysis of individual components of the case study in south Italy

The system savings of each component for the hot water system in south than in north Italy are similar (see Figure 13). In contrast, the improvement potential of the components of the space heating system varies significantly in the north than in the south. The savings potentials are quite lower in the south since the space heating demands are also lower.

5.2.2 Enlarge the energy demand: double people

The double demand is assessed considering 4 instead of 2 people living in the same dwelling.

Step 1 (Figure 9 and Figure 10) of the method is not changing when the number of people living in the dwelling is doubled.

5.2.2.1 Step 2. Estimation of the performance of the initial system

Since the number of people living in the dwelling is doubled, the energy demand for the hot water system is also doubled. The solar contribution is higher with 4 people since the solar sub-system is able to cover higher energy demands during the warmer months (Table 41).

Table 41. Energy demand, solar and non-solar energy demand of the case study with double people (kWh/y).

SANITARY HOT WATER SYSTEM			SPACE HEATING SYSTEM
$E_{HW\ Demand}$	$E_{Sol\ OUTPUT}$	$E_{HW\ Boi\ Non\text{-}sol}$	$E_{SH\ Demand}$
1,274	502	772	17,434

Regarding the space heating system, the energy demand is slightly lower than with 2 people because (see Table 15) the dwelling is the same (same m^2) and SEAS3 considers the heat generated by people.

These new calculations on the energy demand for the hot water and space heating systems and the solar contribution, have been done with SEAS3.

Table 42 and Table 43 show the figures of the energy flows for the sanitary hot water and space heating systems, respectively with 4 people living in the dwelling. Calculations of the energy flows have been assessed with the Excel tool created for this purpose (see section 5.1.1) and modifying the energy demand, the solar contribution and the distribution losses (previously assessed with SEAS3).

Distribution losses (calculated with SEAS3) are higher because more water is circulating through the length of the tubes. However, the storage tank losses (calculated with SEAS3) remain the same since these are calculated based on the nominal volume and dispersion (which remain the same).

Table 42. Energy flows of the sanitary hot water system of the case study with double people (kWh/y).

DISTRIBUTION COMPONENTS (HW)		STORAGE TANK		BOILER HW FUNCTION	
$L_{HW\ Dist}$ (Table 16)	$E_{HW\ Dist\ INPUT}$ (= $E_{ST\ OUTPUT}$)	L_{ST} (Table 16)	$E_{ST\ INPUT}$ (Equation 6)	$E_{HW\ Boi\ OUTPUT}$ (Equation 10)	$E_{HW\ Boi\ INPUT}$ (Equation 5)
1,409	2,683	823	3,506	3,004	4,038

Then, the energy consumption (calculated with the Excel tool) of the sanitary hot water system is higher (4,038 kWh/y) but not double in the case of study with 4 people than in the case study with 2 people (2,795 kWh/y, see Table 18).

Table 43. Energy flows of the space heating system of the case study with double people (kWh/y).

UNDER FLOOR HEATING		DISTRIBUTION COMPONENTS SH		CONTROLS	BOILER SH FUNCTION	
L_{UFloor} (Equation 6)	$E_{UFloor\ INPUT}$ (Equation 5)	$L_{SH\ Dist}$ (Table 17)	$E_{SH\ Dist\ INPUT}$ (Equation 6)	E_{Cont} (Equation 5)	$E_{SH\ Boi\ OUTPUT}$ (Equation 11)	$E_{SH\ Boi\ INPUT}$ (Equation 4)
526	17,960	38	17,998	540	17,458	18,976

In the case of the space heating system, energy flows with 4 people (Table 43) are slighter lower than with 2 people (Table 19) since as mentioned, the heat generated by people is included in the flow calculations.

Figure 20 shows the relative importance of the energy losses of each component of both hot water and space heating systems with the case study with 4 people. Indeed, results are very similar than in Figure 12 and the same conclusions can be drawn.

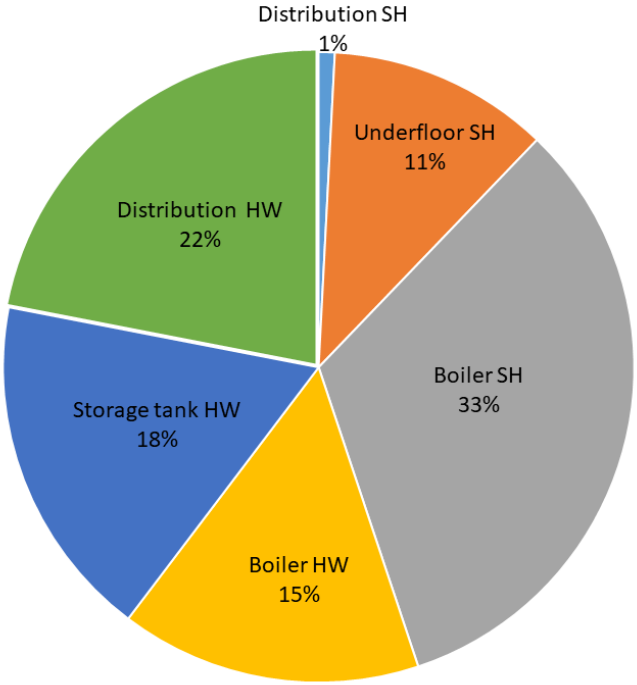


Figure 20. Contribution of each component to the overall energy losses of the case study with double people.

Table 44 shows all the energy performance parameters of the case study for 4 people. The low-emission energy efficiency of the sanitary hot water system is higher than that for 2 people (22.8%, see Table 20) mainly due to the higher use of

renewable energy. Parameters of the space heating system are close to those of the case study for 2 people (Table 20).

Table 44. Energy performance parameters of the heating systems of the case study with double people.

SANITARY HOT WATER SYSTEM			
$E_{HW\ Demand}$ (Table 41) (kWh/y)	$E_{HW\ Boi\ INPUT}$ (Table 18) (kWh/y)	$\eta_{HW\ SYSTEM}$ (Equation 9)	$L_{HW\ system}$ (Equation 7) (kWh/y)
1,274	4,038	31.6%	3,266
SPACE HEATING SYSTEM			
$E_{SH\ Demand}$ (Table 41) (kWh/y)	$E_{SH\ Boi\ INPUT}$ (Table 17) (kWh/y)	$\eta_{SH\ SYSTEM}$ (Equation 9)	$L_{SH\ system}$ (Equation 7) (kWh/y)
17,434	18,976	91.9%	2,083

5.2.2.2 Step 3. Study of the influence of relevant individual components in the overall system

This study is carried out under the same principles and assumptions than in section 5.1.1.3.

Figure 21 shows the influence of individual components on the energy savings of both systems of the case study with 4 people.

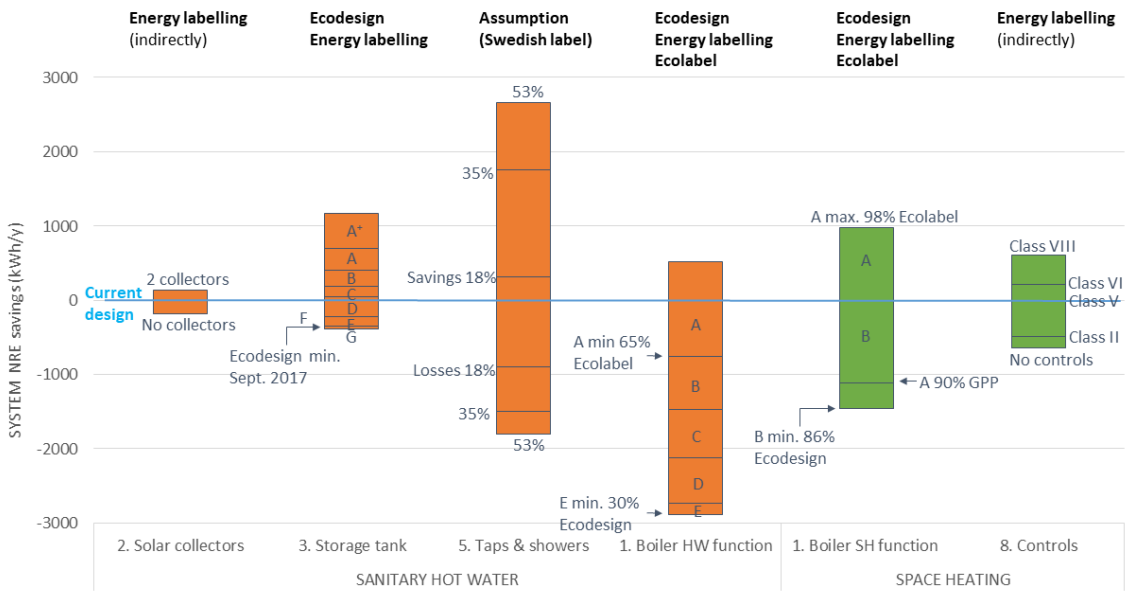


Figure 21. Results of the improvement potential analysis of individual components of the case study with double people

The use of efficient taps and showers could lead to the highest savings (up to 2,663 kWh/y). The second component that allows better savings if it is improved up to the maximum is the storage tank (1,173 kWh/y). Upgrading the space heating function of the boiler up to the maximum, brings 975 kWh/y of savings. Better controls could lead to 608 kWh/y of savings. The hot water function of the boiler brings 514 kWh/y of savings. The solar panels have the least potential for improvement (138 kWh/y).

To summarise, the saving potential of the hot water system with 4 peolple is much higher than in the case study with 2 people (Figure 13) since the energy demand is the double. However, the improvement potential of the space heating system is close to that with 2 people.

5.2.3 Change of technology of the main generator: from a boiler to a heat pump

The heat pump chosen to substitute the boiler is a low-temperature heat pump air-to-water suitable for the size and components of the current design, capable of delivering space heating and sanitary hot water. The choice of this heat pump was done with the aid of the technician and installer of the current heating systems according to the rest of the components and the heating loads of the dwelling.

Then, Step 1 (Figure 9 and Figure 10) of the method is not changing; only the boiler is replaced by an equivalent heat pump.

5.2.3.1 *Step 2. Estimation of the performance of the initial system*

The energy heating demands for both the sanitary hot water and the space heating systems do not change from the design of section 5.1.1.2 (see Table 15 and Figure 11).

The heat pump has a water heating energy efficiency of 87,5% (energy label A) and a space heating energy efficiency of 155% (energy label A^{++}) according to the manufacturer and Regulation 813/2013. The rest of components remain the same.

Then, the energy flows of the sanitary hot water system are the same as in the current design (Table 18 and Table 19) except for the energy consumption of the heat pump (Table 45 and Table 46). The energy consumption of the heat pump is lower than that of the boiler since its efficiency is higher.

Table 45. Energy flows of the sanitary hot water system of the case study with a heat pump (kWh/y).

DISTRIBUTION COMPONENTS (HW)		STORAGE TANK		HEAT PUMP DHW FUNCTION	
$L_{HW\ Dist}$ (Table 16)	$E_{HW\ Dist\ INPUT}$ (= $E_{ST\ OUTPUT}$)	L_{ST} (Table 16)	$E_{ST\ INPUT}$ (Equation 6)	$E_{HW\ HP\ OUTPUT}$ (Equation 10)	$E_{HW\ HP\ INPUT}$ (Equation 5)
1,018	1,655	823	2,478	2,079	2,376

Table 46. Energy flows of the space heating system of the case study with a heat pump (kWh/y).

UNDER FLOOR HEATING		DISTRIBUTION COMPONENTS SH		CONTROLS	HEAT PUMP SH FUNCTION	
L_{UFloor} (Equation 6)	$E_{UFloor\ INPUT}$ (Equation 5)	$L_{SH\ Dist}$ (Table 17)	$E_{SH\ Dist\ INPUT}$ (Equation 6)	E_{Cont} (Equation 5)	$E_{SH\ HP\ OUTPUT}$ (Equation 11)	$E_{SH\ HP\ INPUT}$ (Equation 5)
545	18,630	38	18,668	560	18,108	11,534

Figure 22 shows the relative importance of the energy losses of each component of both hot water and space heating systems of the case study with a heat pump. Losses of the space heating function of the heat pump are zero and those ones from the water heating function are lower (from 715kW to 297kW), so that the losses of the rest of the components become relatively higher with respect the current design (Figure 12). The distribution and the storage tank are the components with the highest losses. The underfloor heating has also relevant losses (20%).

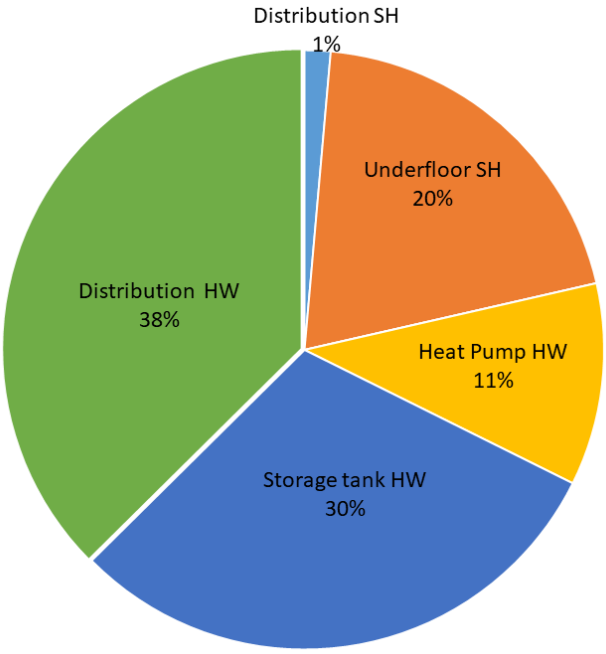


Figure 22. Contribution of each component to the overall energy losses of the case study with a heat pump.

Table 47 shows the energy performance parameters of the case study with a heat pump. The low-emission energy efficiency of the systems with a heat pump is higher than that with the boiler (22,8% for the hot water system and 91,9% for the space heating, see Table 20) due to the higher efficiency of the heat pump with respect the boiler. Therefore, losses are also much lower than with the boiler, especially in the space heating system.

Table 47. Energy performance parameters of the heating systems of the case study with a heat pump

SANITARY HOT WATER SYSTEM			
$E_{HW\ Demand}$ (Table 15) (kWh/y)	$E_{HW\ Boi\ INPUT}$ (Table 18) (kWh/y)	$\eta_{HW\ SYSTEM}$ (Equation 9)	$L_{HW\ system}$ (Equation 7) (kWh/y)
637	2,376	26,8%	2,138
SPACE HEATING SYSTEM			
$E_{SH\ Demand}$ (Table 15) (kWh/y)	$E_{SH\ Boi\ INPUT}$ (Table 17) (kWh/y)	$\eta_{SH\ SYSTEM}$ (Equation 9)	$L_{SH\ system}$ (Equation 7) (kWh/y)
18,085	11,534	156,8%	583

5.2.3.2 *Step 3. Study of the influence of relevant individual components in the overall system*

Regarding the water heating energy efficiency, the performance levels which applies with a heat pump is the same as in the current design (Table 21). However, the space heating function of the heat pump is designed for low-temperature applications as is the underfloor heating. The Regulation 811/2013 specifies two different tables of efficiencies and energy classes for conventional (Table 22) and low-temperature space heaters (Table 48).

Table 48. Seasonal space heating energy efficiency classes of low-temperature heat pumps for low-temperature applications

Energy labelling (Regulation 811/2013)		Other product policies
Energy efficiency class	Minimum seasonal space heating energy efficiency	
A^{+++}	$\eta_{SH} \geq 175$	
A^{++}	$150 \leq \eta_{SH} < 175$	155% - Heat pump (extended analysis of the case study)
A^{+}	$123 \leq \eta_{SH} < 150$	
A	$115 \leq \eta_{SH} < 123$	
B	$107 \leq \eta_{SH} < 115$	
C	$100 \leq \eta_{SH} < 107$	100% - minimum Ecodesign requirements (EC, 2013d)
D	$61 \leq \eta_{SH} < 100$	Phased out
E	$59 \leq \eta_{SH} < 61$	Phased out
F	$55 \leq \eta_{SH} < 59$	Phased out
G	$\eta_{SH} < 55$	Phased out

It should be noted that the low-temperature heat pump itself has a seasonal space heating above 100% (without being combined in a package with solar device or temperature control as happens with conventional space heaters). It has higher thresholds to reach each label class than conventional space heaters (see Regulation 811/2013). Nor EU Ecolabel nor GPP have a specific product group for low-temperature water heaters so that these are not included in Table 48.

Figure 23 shows the influence of individual components on the energy savings of both systems of the case study with a heat pump instead of a boiler. For simplification of the figures, Figure 23 shows only heat pump SH classes A^{+}, A^{++} and A^{+++}.

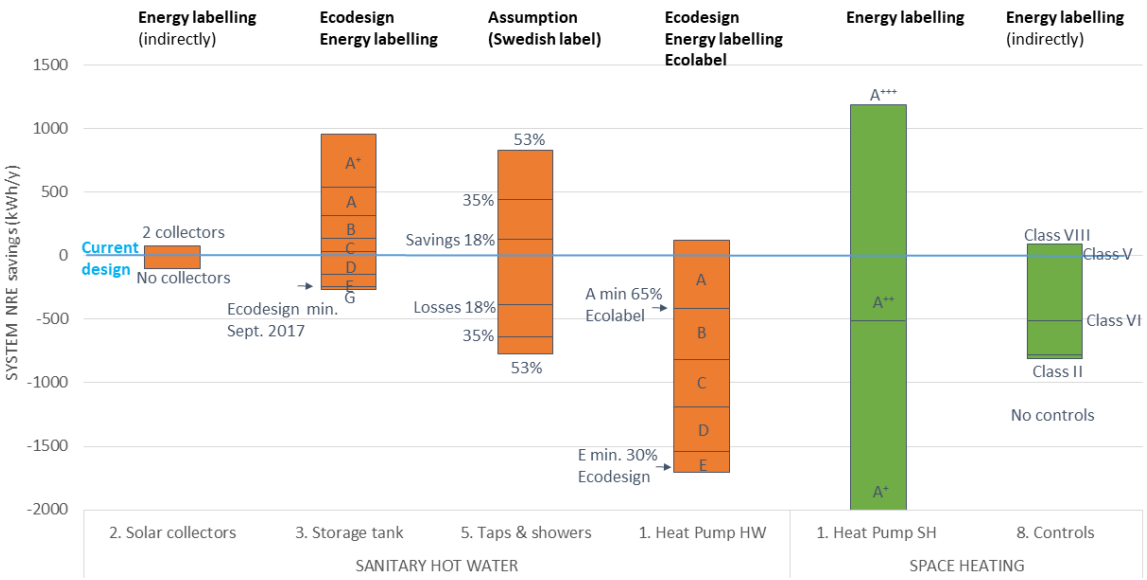


Figure 23. Results of the improvement potential analysis of individual components in the case study with heat pump

The most influent component is the heat pump in its space heating function which could achieve up to 1.183kW/y of savings when it is improved to class A^{+++}. The second component that allows better savings if it is improved up to the maximum class is the storage tank (960 kWh/y). Better taps and showers could lead to 830 kWh/y of savings.

In conclusion, the space heating system with the chosen low-temperature heat pump achieves much more savings than the current design of the case study (Figure 13). Distribution and the storage tank are the components which produce the highest losses in contrast to the current design that it was the boiler.

5.3 Summary and discussion of the extended analysis of the case study

In the extended analysis of the case study, some initial conditions are modified in order to check if the method is still valid. These are the location, the energy demand and the technology. In particular:

1. Changing location: from north to south Italy.
2. Enlarging heating demand: double people.
3. Substituting the boiler by a heat pump.

Table 49 shows how the energy performance parameters vary with respect the current design. Each of these cases have been discussed in detail in previous sections.

Table 49. Summary of energy performance parameters of the extended analysis of the case study

ENERGY PARAMETERS	Current design	Changing location: from north to south Italy	Enlarging energy demand: double people	Substituting the boiler by a heat pump
SANITARY HOT WATER				
Energy demand (kwh/y)	637	637	1,274	637
Energy losses (kwh/y)	2,557	2,375	3,266	2,138
Energy consumption (kwh/y)	2,795	2,522	4,038	2,376
Low-emission energy efficiency (%)	22.8	25.3	31.6	26.8
SPACE HEATING				
Energy demand (kwh/y)	18,085	5,561	17,434	18,085
Energy losses (kwh/y)	2,158	697	2,083	583
Energy consumption (kwh/y)	19,683	6,084	18,976	11,534
Low-emission energy efficiency (%)	91.9	91.4	91.9	156.8

Table 50 summarises the energy losses in kWh/y and % of each component of the current design and the extended analysis of case study. What is important here is to highlight those components with highest losses which could be balanced out by renewable sources. In the current design, changing location from north to south and enlarging the energy demand by doubling the people, the greater energy losses are due mainly to the distribution, the boiler and the storage tank. The fact of substituting the boiler by a heat pump makes the heat generator to be greatly improved to the point to be the fourth component with highest losses and the underfloor heating to become the third most important component. A limitation of the study of the system energy losses per component (Table 50) is that this analysis does not consider taps and showers since the assumption made initially was that taps and showers do neither save nor lose any energy.

Table 50. Summary of energy losses of components of the extended analysis of the case study (kWh/y and %)

	Current design		Changing location: from north to south Italy		Enlarging energy demand: double people		Substituting the boiler by a heat pump	
SANITARY HOT WATER								
Distribution water heating	1018	22%	1018	33%	1018	22%	1018	38%
Storage tank	823	17%	711	23%	823	18%	823	30%
Boiler/Heat pump (water heating function)	715	15%	646	21%	715	15%	297	11%
SPACE HEATING								
Boiler (space heating function)	1575	33%	487	16%	1518	33%	0	0%
Underfloor heating	545	12%	172	6%	526	11%	545	20%
Distribution space heating	38	1%	38	1%	38	1%	38	1%

With regard the improvement potential at system level, Table 51 summarises results if each component individually was upgraded up to the maximum performance level.

Table 51. Summary of the improvement potential of each component of the extended analysis of the case study (kWh/y of savings)

COMPONENTS	Current design	Changing location: from north to south Italy	Enlarging energy demand: double people	Substituting the boiler by a heat pump
SANITARY HOT WATER				
Solar panels	78	52	138	78
Storage tank	960	901	1173	960
Taps and showers	981	912	2663	830
Boiler/Heat pump (water heating function)	259	263	514	124
SPACE HEATING				
Boiler (space heating function)	1012	343	975	1186
Temperature controls	626	253	608	92

Table 52 has been built according to Table 51 and shows how the order of the components to be improved first, change with respect the current design. In all cases

the space heating function of the boiler, the taps and showers and the storage tank are among the three first components to be improved in that order to get the greater savings. These results are consistent with those obtain from Table 50 in which the boiler and the storage tank would be the first components to be improved according to its contribution to system energy losses. Regarding the distribution and the underfloor losses, it is unlikely (as stated in section 5.1.1.3) that a re-design considers to change or to modify (e.i. by adding isolation materials) these components.

Table 52. Order of components to be improved in the extended analysis of the case study (from most to least savings)

ORDER OF IMPROVEMENT	Current design	Changing location: from north to south Italy	Enlarging energy demand: double people	Substituting the boiler by a heat pump
1	Boiler (space heating function)	Taps and showers	Taps and showers	Boiler (space heating function)
2	Taps and showers	Storage tank	Storage tank	Storage tank
3	Storage tank	Boiler (space heating function)	Boiler (space heating function)	Taps and showers
4	Temperature controls	Boiler (water heating function)	Temperature controls	Boiler (water heating function)
5	Boiler (water heating function)	Temperature controls	Boiler (water heating function)	Temperature controls
6	Solar panels	Solar panels	Solar panels	Solar panels

Changing location from north to south Italy is in principle an unlikely case, since this is not depending on the designers' choice. As expected, the reduction of the energy consumption in the space heating system in south Italy is significant (19,683 in the north and 6,084 kWh/y in the south) since the energy demand in that region (Palermo) is also quite lower. A slighter lower system energy efficiency of the space heating system (91.9% in the north and 91.4% in the south) can be explained by the worse use of the capacity of the boiler which could make the designer to choose a more appropriate boiler according to the new heating loads of the dwelling. Higher energy savings due to the use of solar panels could have been expected in south Italy since the solar contribution is higher (64.5% in the north and 77.2% in the south). However, only the hot water system is run with this renewable energy and this system requires quite lower energy input than the space heating system (637 kWh/y for water heating versus 5,561 kWh/y for space heating) even in a region with quite less space heating energy demands than in the north (18,085 in the north and 5,561 kWh/y in south Italy). On the other hand, the number of people is the same (2 people) and so that also the hot water requirements (same water heating energy demand).

Enlarging the heating demand of the dwelling by doubling the people living in the house increases the water heating demands in the same proportion. However, the energy consumption of the hot water system is not doubled due to the higher solar contribution. Then, in the hot water system with 4 people, it is optimised the solar harvesting of the collectors during the summer and also the capacity of the boiler since the boiler works at full load longer time. In contrast, the space heating system with 4 people barely changes. The space heating energy demand is slightly lower than with 2 people because the dwelling is the same (same m^2) and SEAS3 considers the heat generated by people, and thus the energy losses and the energy consumption are also slightly lower.

Usually, a change in the technology of the heat generator implicitly implies to choose a more efficient device (such as substituting the boiler by a heat pump) and thus, to improve the system efficiency and reducing the energy consumption. This is shown in the space heating system of the heat pump case in which the higher efficiency of the boiler is quite higher (155% with the heat pump versus 92% with the boiler) and consequently the energy losses and energy consumption lower and the system efficiency higher. Substituting the boiler by an equivalent heat pump does not modify a lot results in the sanitary hot water system with respect the current design with the boiler since the efficiency of the heat pump is slighter higher (85.7%) than the one from the boiler (74.4%). Although the same legislation is affecting the boiler and the heat pump, in this case, the energy efficiency scale is different (see Table 48). These higher figures in the energy efficiencies (higher than 100%) and classes of the heat pump with respect the boiler could be interpreted from the point of view of some authors (Pérez-Lombard, 2008) which state that heat pumps could be considered as a kind of renewable energy technology.

In conclusion, results of the analysis of the extended case study show that the method proposed in section 4 works properly when variables which in principle are fixed in the original method, are modified. However, results depend on the initial hypothesis made such as taking for granted assumptions made by SEAS3 (e.g. distribution losses do not change when changing location or taking into account the heat generated by people) or by assuming that taps and showers do neither save nor loose energy.

6. ANALYSIS OF ANOTHER SYSTEM APPROACH IN PRODUCT POLICIES: THE PACKAGE LABEL

6.1 Introduction

As stated in section 1, European sustainable product policies (such as Ecodesign or Energy labelling Directives) have been applied in the EU in the last years, especially in energy-using and energy-related products. Their impacts in markets and their effectiveness (energy savings) have been demonstrated in different product categories (e.g. washing machines, fridges, etc.). These policies have been continuously adapting to the features of the new product groups through broadening their scope from a strict product approach, to the extended product and system approaches. In this regard, section 2.5 analyses product policies initiatives in which the system approach has been implemented (e.g. heating systems). However, such product policies have been not been implemented for long time in HVAC systems. In particular, the case of the package concept of heating systems is a recent approach which needs yet time to settle in order to prove its energy saving potential.

This section is presented through a scientific paper recently published in *Energies* Journal. On the one hand, due to my background on policy (see section 3.1), it was appropriate to further analyse and discuss the system approach of EU environmental product policies. On the other hand, following the research line of this PhD, the goal was to investigate how the fresh package concept of heating systems (set in Regulations 812/2013, 811/2013 and 1187/2015) could support the design of more performing systems.

The paper presents a systematic analysis on the evolution of the different system approaches of EU product policies from an engineering point of view. In particular, it analyses in detail the recently introduced and implemented package label (in heating systems) which is a modular approach, standing between the extended product and the system approaches. This analysis includes an application of the calculation of the package label into a real case study which contains a solar hot water system and a space heating system (the same as in section 5). Lessons learnt and discussion on the calculation method of the package label are brought from results of the case study. Finally, the paper concludes with the links between the building-related product policies and the Energy Performance of Building Directive (EPBD)[2].

Finally, this section includes an additional discussion (section 6.3) comparing the method for calculating the system performance in the package label against the method proposed in section 4. This is done from results of the same case study using both methods.

[2] The analysis of the package concept of heating systems of EU product policies and the link between building-related product policies and EPBD, are topics not analysed in detail before in previous sections of this manuscript.

6.2 From product to system approaches in European sustainable product policies: analysis of the package concept of heating systems in buildings.

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From Product to System Approaches in European Sustainable Product Policies: Analysis of the Package Concept of Heating Systems in Buildings

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Abstract: Different policies with the goal of reducing energy consumption and other environmental impacts in the building sector coexist in Europe. Sustainable product polices, such as the Ecodesign and Energy Labelling Directives, have recently broadened the scope of their target product groups from a strict product approach to extended product and system approaches. Indeed, there is a potential for greater savings when the focus is at a system level rather than on regulating individual products. Product policies for space and water heating systems have recently introduced and implemented the package label, which is a modular approach, standing between the extended product and the system approaches. This paper presents a systematic analysis of the different system approaches of various policies from an engineering perspective. It analyses in detail the package concept and its features through a practical application using a real case study. It focuses on how the package concept can support decisions made in the building design phase and, in particular, how can support the choice of appropriate components based on estimating system performances. This brings building engineers and regulators closer regarding the use of more consistent data on energy performance. Finally, this paper highlights the need to improve the alignment of the building-related product policies with the Energy Performance of Buildings Directive.

Keywords: product policies; heating systems; buildings

1. Introduction

Different European policy instruments with the goal of reducing energy consumption in the building sector coexist. While macro-policies, such as the Energy Efficiency Directive or the Energy Performance of Buildings Directive (EPBD) set global (by country, by sector, etc.) energy targets, micro-policies, such as the Ecodesign Directive or the Energy Labelling Directive, set specific energy targets (by product groups).

At the macro level, the Roadmap to a Resource Efficient Europe mentions that improved construction and use of buildings in the European Union (EU) would influence 42% of our final energy consumption [1]. Improvements in the energy efficiency of buildings could contribute to the 80–95% target of reducing greenhouse gas (GHG) emissions by 2050 compared with 1990 [2]. Heating and cooling are the EU's biggest energy-consuming sectors, representing 50% (546 Mtoe) of final energy consumption in 2012, and much of it is wasted through insufficient insulation or inefficient equipment in buildings, among other causes [3]. The implementation of the EPBD promotes energy efficiency by reducing the energy used to maintain indoor environmental quality through

heating and cooling, ventilation, lighting and operating appliances, and by the use of renewable energy in buildings [4]. The EPBD requires Member States to set minimum requirements with respect to overall energy performance on the proper installation, equipment size, adjustment and control of new, replacement and upgraded technical building systems.

At the micro level, European sustainable product policies, such as the Ecodesign and Energy Labelling Directives, EU Green Public Procurement and the EU Ecolabel have the common goal of making the European market more sustainable [5]. Indeed, they have been very successful in improving the energy efficiency of energy-using products such as electric motors, washing machines, refrigerators or dishwashers. The Ecodesign and Energy Labelling Directives' requirements for space and water heaters are expected to bring annual energy savings of 600 TWh and reduce CO_2 emissions by 135 million tonnes by 2030 [3]. These product policies initially addressed individual products, adopting a strict product approach. However, the importance of considering additional products or components that significantly influence total energy efficiency was soon realised. In fact, there is great energy-saving potential when the focus is at a higher level, rather than only on regulating individual products.

Ecodesign Regulation 640/2009 regarding electric motors [6] was the first EU product policy to apply an extended product approach, which consists of extending the system boundaries to include other products (e.g., drives for a motor) that influence the performance of the product under study (e.g., the overall energy efficiency of the electric motors). Recently, a system approach has also been applied to electric motors used in ventilation units (e.g., Ecodesign Regulation 1253/2014 in ventilation units [7]), which considers all or some of the components (motor, drive, casing, ducts, controls, etc.) needed to deliver a service. Similarly, product polices on lighting [8] have also implemented a system approach.

Therefore, EU product policies have been broadening the scope of their target product groups from a product approach to a more system approach. The product approach calculates the energy performance of one product (included in a product group), while the extended product approach calculates the performance of one product (included in a main product group) based on its function and could include the influence of other products. In contrast, the system approach calculates the performance of a system that delivers a service, and this system is considered to be the product group itself. Recently, energy labelling of water and space heating systems (e.g., Regulations 812/2013 [9] and 811/2013 [10]) have introduced and implemented the package label, which includes the energy efficiency of a group of certain heating components (water/space heaters and solar device and/or temperature control). This paper focuses on this package concept, in particular on heating systems, and the way it calculates the package energy efficiency which is different from the extended product and system approaches. This package concept is useful for designers, since it allows them to choose the product performance that will make up the legal package label.

The design of efficient heating systems is a huge challenge, since buildings are complex systems, composed of many and very heterogeneous components, materials and devices that interact with each other, the outside environment and their users [11]. Indeed, the decisions made in the building design phase [12], and in particular on the components chosen for the system, are crucial to avoid major environmental impacts. System designers need to satisfy heating demands, calculate heat loads and achieve system optimisation that will allow performances to be predicted [13]. Many engineering methods have been developed for the system level [14]. In this regard, EU product policies could be useful to design efficient heating systems [15]. Nevertheless, the way in which product policies calculates the energy efficiency and the real energy performance of the whole heating system can vary greatly. There is still a technological gap between building designers and regulators that needs to be filled to ensure the achievement of overall energy efficiency objectives [16].

This paper presents a systematic analysis of different system approaches of various policies, taking an engineering perspective. The aim of the paper is to investigate how the package concept of EU product policies helps in estimating the system performance and supports the design work. It considers the example of the package concept in heating systems in buildings as the main basis of

the investigation. The paper also discusses the challenges for European environmental policies to align macro- and micro-level policies more closely.

The method followed in carrying out this research work had two steps. Firstly, the package concept was analysed theoretically through examination of relevant EU Regulations and then analysed with regard to the product, extended product and system approaches. Secondly, the package concept was applied to a real case study, which includes water and space heating systems. The analysis of the case study represents how data from product policies can be useful in a design context. This second step therefore contributes to the analysis of the package concept from a practical point of view and it brings some points of discussion (advantages, limitations and improvement potential) regarding the methodology used by the package concept.

The paper is presented in five sections. Section 1 describes the background and introduces the product, extended product and system approaches, and the package concept of the EU product policies. Section 2 includes the theoretical analysis of the package concept and its calculation methods, in particular those for heating systems in Regulations 812/2013 [9], 811/2013 [10] and 1187/2015 [17]. Section 3 analyses the practical application of the package concept in a real case study, which includes water heating and space heating systems. Lessons learnt from the case study and the advantages and limitations of the package concept are discussed in Section 4. Finally, the paper concludes in Section 5.

2. Analysis of the Package Concept in EU Energy Labelling Regulations for Heating Systems

2.1. The Origin of the Package Concept

The package label appeared first in Regulations 812/2103 [9] and 811/2013 [10] on space and water heaters, respectively, and later in Regulation 1187/2015 [17] on solid fuel boilers. In Regulations 811/2013 and 812/2013, the package concept was introduced very late in the policy process development, during the consultations prior to the adoption of the delegated act [18]. Suppliers of solar devices and temperature controls (often small and medium-sized enterprises and consumer organisations) were not able to communicate the benefits of their products by providing information on their products in an isolated manner (as part of the product fiche of heaters) because: (1) their products are usually placed on the market by their clients (dealers or installers) and therefore consumers do not have easy access to this information and (2) the information on the potential energy savings of these devices can be understood only when they are used in combination with heaters.

The provision of information on solar devices and temperature controls to consumers was initially too limited and the package concept was introduced to overcome this market barrier [18]. The package label and fiche allow the independent provision of information by suppliers and dealers. The calculation is simple, meaning that performances provided by the manufacturer of the solar device and/or temperature controls can be combined easily with the efficiency provided by the heater manufacturer. The dealer can then make up the package label according to separate product fiches provided by suppliers of heaters, solar devices and temperature controls. In this way, it is possible to avoid discrimination against configurations offered by dealers/installers consisting of parts that were placed on the market individually, compared with the identical configuration offered by a single supplier/dealer [19]. In addition, consumers are able to compare equivalent systems delivering the same service (e.g., water heating).

2.2. From Product, to Extended Product and System Approaches

The strict product approach of product policies has evolved towards the inclusion of a greater number of products in two directions (see Figure 1); on the one hand, to the extended product approach (e.g., motors) and the system approach (e.g., lighting), and on the other hand, to the package concept (e.g., heating). The package concept is a type of modular approach. Depending on the number of products included, this modular approach lies between the extended product approach and the (sub-)system approach (Figure 1), since it could include a few or several products.

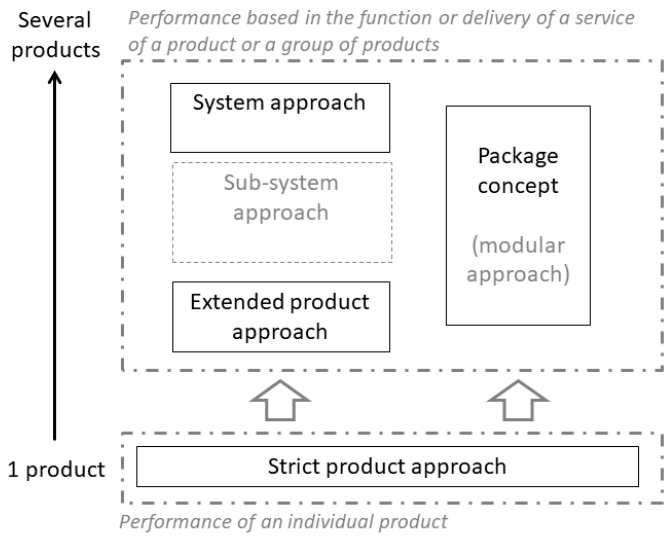

Figure 1. Schematic positioning of the different approaches of EU product policies in terms of the complexity of the system of products considered.

The difference between the extended product and system approaches on one hand and the package concept on the other hand is that the package efficiency is made up of a group of products whose presence and influence can be easily identified (Figure 2). For instance, the package label shows graphically all the components included in a package, whereas labels in the extended product or system approaches show the energy performance without indicating whether or not the influence of other components was included in the calculation.

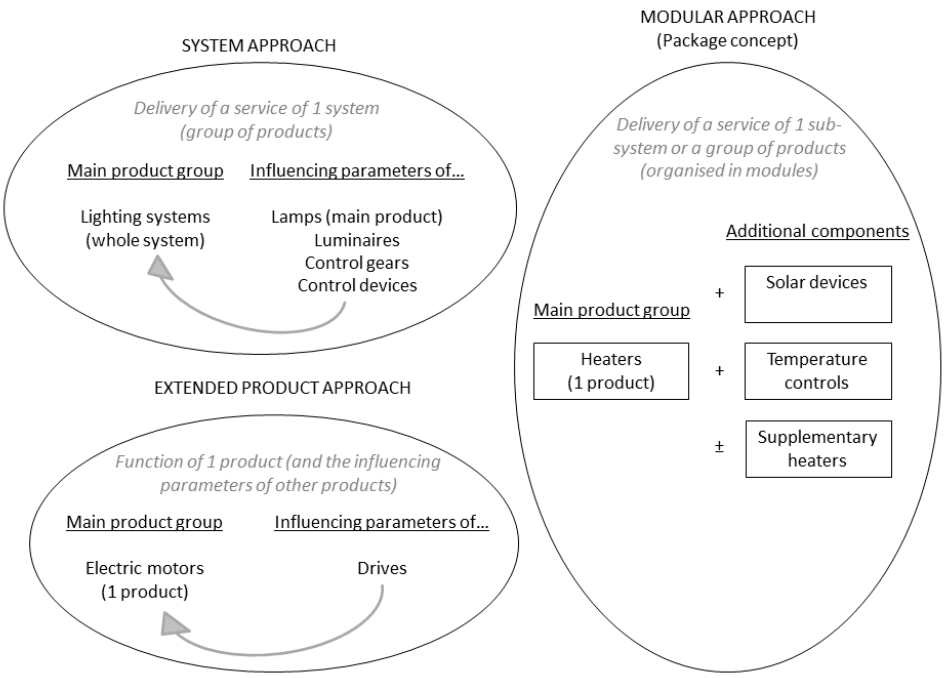

Figure 2. Differences between the calculation methods of the extended product, system and modular approaches (with examples).

The energy efficiency of the extended product and system approaches is calculated using a formula that includes the function or service delivered by the main product as well as the influencing

parameters of other components. The main product is that for which the regulation in question was initially created. The components are the additional products that have been included in the calculation of the efficiency of the main product. The energy efficiency of a package is the sum (positive and negative) of the efficiency of the main product group and that of certain additional products or components as set in the EU Regulations (Figure 2).

Therefore, the calculation method used to determine the package efficiency is flexible enough to allow the addition of new (individual) components regardless of the manufacturer. In contrast, the calculation methods used in product policies, which apply the extended product or system approaches (e.g., motors and lighting systems), could not incorporate additional components easily, since the whole formula would have to be revised.

The implementation of the package concept involves different actors: manufacturers, suppliers, dealers, installers, end users and system designers. Firstly, manufacturers and/or importers have to provide information regarding the performance of the products (and sometimes of packages) they put on the EU market, since the Ecodesign and Labelling Directives are mandatory instruments. If a water or space heater is placed on the market together with solar devices and/or temperature controls by the same dealer, this one has to provide the package label of this group of components. In addition, although these heating components have been purchased separately, the installer must also provide the package label. Therefore, end users and consumers are able to make informed choices and carry out fair comparisons on the heating products and packages they purchase. Finally, building engineers are able to take informed design decisions at the system level and, although they are not bound by the package label regulations, they are important players in the global chain and are responsible for the proper and efficient design of heating systems. They should provide the technical specifications for the procurement process, such as the performance of products and packages (i.e., energy class) to be installed in the heating system.

2.3. Products' Scope and Calculation Schemes of the Package Concept

Figure 3 summarises the scope of the different product groups defined in EU regulations that address packages.

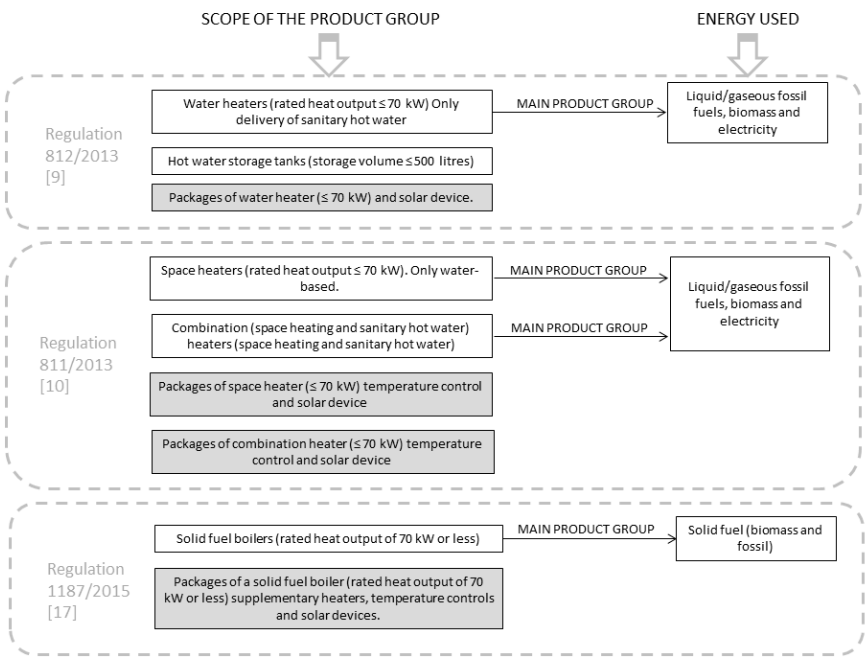

Figure 3. Scope of the EU Regulation which include the package concept.

Some of the products/packages affected by these regulations provide only water heating or space heating, while others provide both water and space heating (combination heaters). All of them include heaters providing heat to water-based central heating systems for space heating purposes and/or for delivering hot drinking and sanitary water (i.e., air or other means of heating distribution are out of scope) and use very heterogeneous technology (e.g., electric/gas boilers, heat pumps, cogeneration heaters) using renewable (e.g., biomass, solar) and non-renewable energy sources (e.g., liquid, gaseous or solid fossil fuels, electricity) (Figure 3).

Table 1 shows which products are included in the packages of the EU regulations cited in Figure 3 (third and fourth column of Table 1). According to these regulations, a boiler is a water, space or combination heater that uses fossil fuels, biomass fuels or electricity (using the Joule effect in electrical resistance heating elements). A heat-pump-based water, space or combination heater uses ambient heat from an air source, water source or ground source, and/or waste heat for heat generation and may be equipped with one or more supplementary heaters. The definition of a solar device includes not only the solar collectors, but also solar hot storage tanks and pumps in the collector loop of the solar sub-systems.

Table 1. Overview of the efficiency package calculation schemes in EU regulations.

EU Regulation	Where the Calculation Method Is Specified in the Regulation	Main Product/Preferential Heater	Additional Components	Result Offered by the Package
Regulation 812/2013 [9]	*Annex 4* of regulation, *Figure 1*	Water heater	Solar device	Water heating energy efficiency
Regulation 811/2013 [10]	*Annex 4* of regulation, *Figure 1*	Space and combination heater	Solar device Temperature control Supplementary boiler Supplementary heat pump	Seasonal space heating energy efficiency
Regulation 811/2013 [10]	*Annex 4* of regulation, *Figure 2*	Cogeneration space heater	Solar device Temperature control Supplementary boiler	Seasonal space heating energy efficiency
Regulation 811/2013 [10]	*Annex 4* of regulation, *Figure 3*	Heat pump space and combination heaters	Solar device Temperature control Supplementary boiler	Seasonal space heating energy efficiency
Regulation 811/2013 [10]	*Annex 4* of regulation, *Figure 4*	Low-temperature heat pumps	Solar device Temperature control Supplementary boiler	Seasonal space heating energy efficiency
Regulation 811/2013 [10]	*Annex 4* of regulation, *Figure 5*	Boiler combination heaters and heat pump combination heaters	Solar device	Water heating energy efficiency
Regulation 1187/2015 [17]	*Annex 4* of regulation, *Figure 1*	Primary solid fuel boiler	Solar device Temperature control Supplementary boiler	Energy efficiency index

The calculation schemes included in these regulations (second column of Table 1) specify the calculation method of the package energy efficiency and the package efficiency class according to parameters of the main product and additional components (see example in Figure 4). When the "main product" is combined with at least one of the "additional components" in Table 1, the package efficiency/label shall be calculated. The results of the calculations for each of these schemes provide the water heating energy efficiency, the space heating energy efficiency or the energy efficiency index (last column of Table 1), depending on the result type the package offers.

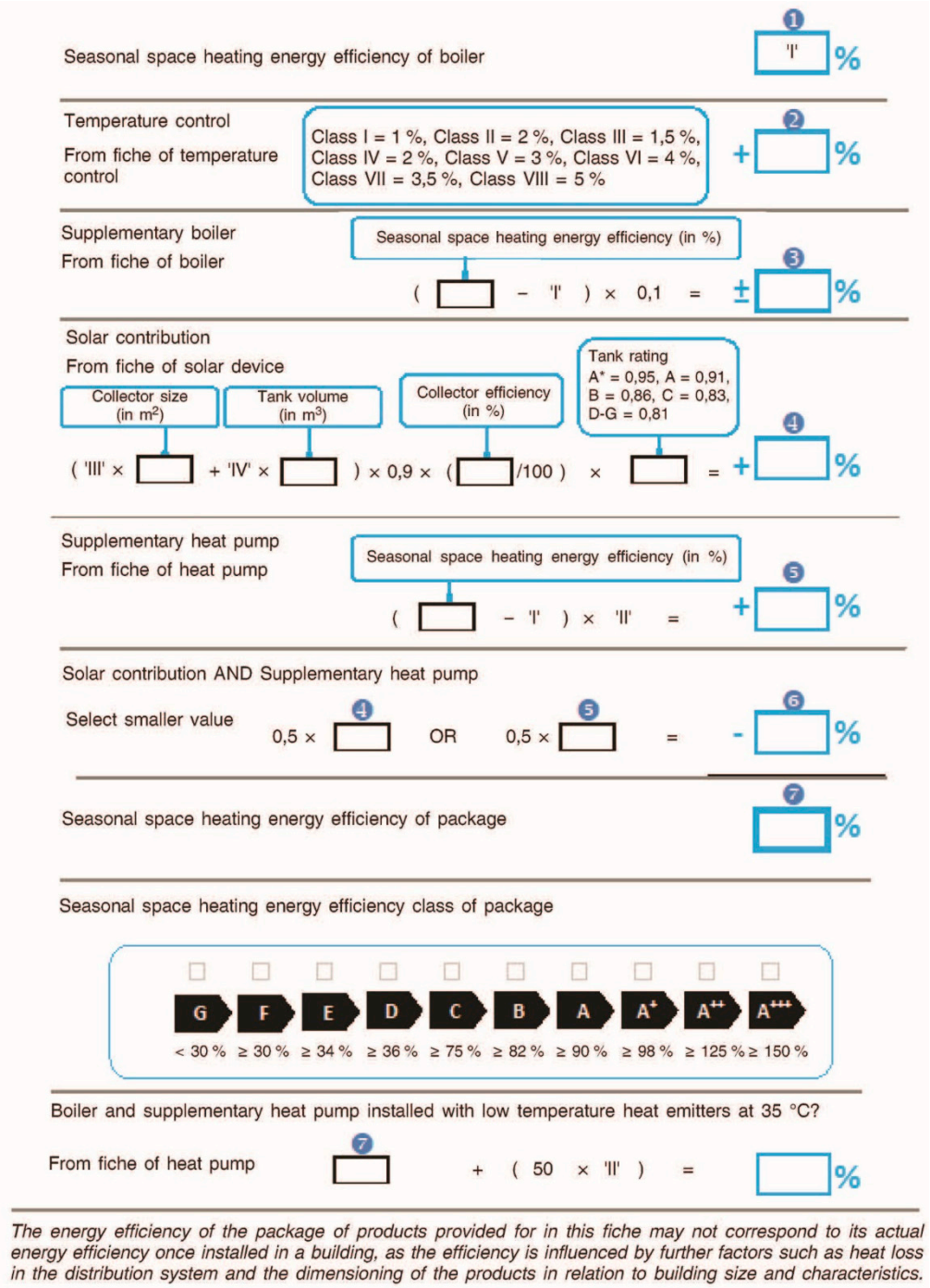

Figure 4. Illustration of *Figure 1* (space and combination heaters) of Regulation 811/2013 (*Annex 4*) [10] © European Union, http://eur-lex.europa.eu/, 1998–2017.

Figure 4 shows as an example the section of Regulation 811/2013 that explains how to calculate the package energy efficiency and how to set the energy class for a package of a combination heater with temperature control, supplementary heaters and solar devices.

Table 2 analyses in detail each of the calculation schemes (*Figures* of *Annex 4* of Regulations 812/2013, 811/2013 and 1187/2015). It shows the parameters that might be involved in the calculation of the energy efficiency of each type of package.

Table 2. Technical parameters involved in the calculation of the package energy efficiency.

Category of Product	Products	Product Parameters	Intermediate Parameters	Package Parameters
Main product	Water heaters, space and combination heaters and solid fuel boilers	Water/seasonal space heating energy efficiency (%) Reference energy, Q_{ref} (KWh)	–	Water/seasonal space heating) energy efficiency (%)
Solar devices	Solar collectors	Collector area (m^2) Collector efficiency (%)	Annual auxiliary electricity consumption, Q_{aux} (kWh/year), and annual non-solar heat contribution, Q_{nonsol} (kWh/year)	Solar contribution (%)
	Solar pump	Power consumption (W) Standby power consumption (W)		
	Solar storage tank	Storage volume (m^3) Energy class (A, B, C, etc.) or standing losses (W)		
Controls	Temperature controls	Class (I, II, III, IV, V, VI, VII)	–	Contribution to seasonal space heating (%)
Supplementary heaters	Supplementary boiler or heat pump	Seasonal space heating energy efficiency (%)	–	Parameters of the supplementary boiler (%)

All the calculation schemes (Figures from the Regulations) follow a similar structure in which the package parameters (last column in Table 2) are added or subtracted to obtain the overall energy efficiency (or index) of the package (see example in Figure 4). The package parameters show the contribution of the products to the package efficiency. In some cases, the calculation of the package efficiency (or index) is provided not only for average but also for colder and warmer climates in percentages ("average climate conditions", "colder climate conditions" and "warmer climate conditions" mean the temperature and global solar irradiance conditions characteristic of the cities of Strasbourg, Helsinki and Athens, respectively). The energy class (A^{++}, A^{+}, A, B, etc.) of the package is set for each type of package (specific Figure of each Regulation) according to the package energy efficiency ranges.

The energy efficiency (or index) might be higher than 100% because the efficiencies of solar devices and/or temperature controls are added to the efficiency of the main product group. Efficiencies higher than 100% are accepted in the definition of low-emission energy efficiency [20], which does not consider the renewable energy consumption, to minimise the non-renewable consumption. This type of energy efficiency has been used commonly in building-related policies oriented towards low-emission designs. This has been an effective way in which the package concept of EU product policies has rewarded renewable energy sources and energy-saving components. One of the aims of these packages is to assess the benefits of using solar devices and temperature controls together with heaters.

3. Application of the Package Concept to a Real Case Study

This section presents how the package energy efficiency and class is calculated for a real domestic hot water (DHW) system, including solar devices and a space heating (SH) system for a 60 m^2 dwelling. Both systems have the same gas boiler (Figure 5). In the DHW system, the boiler is a backup of the solar sub-system, whereas in the space heating system, it provides all the hot water needed for the space heating.

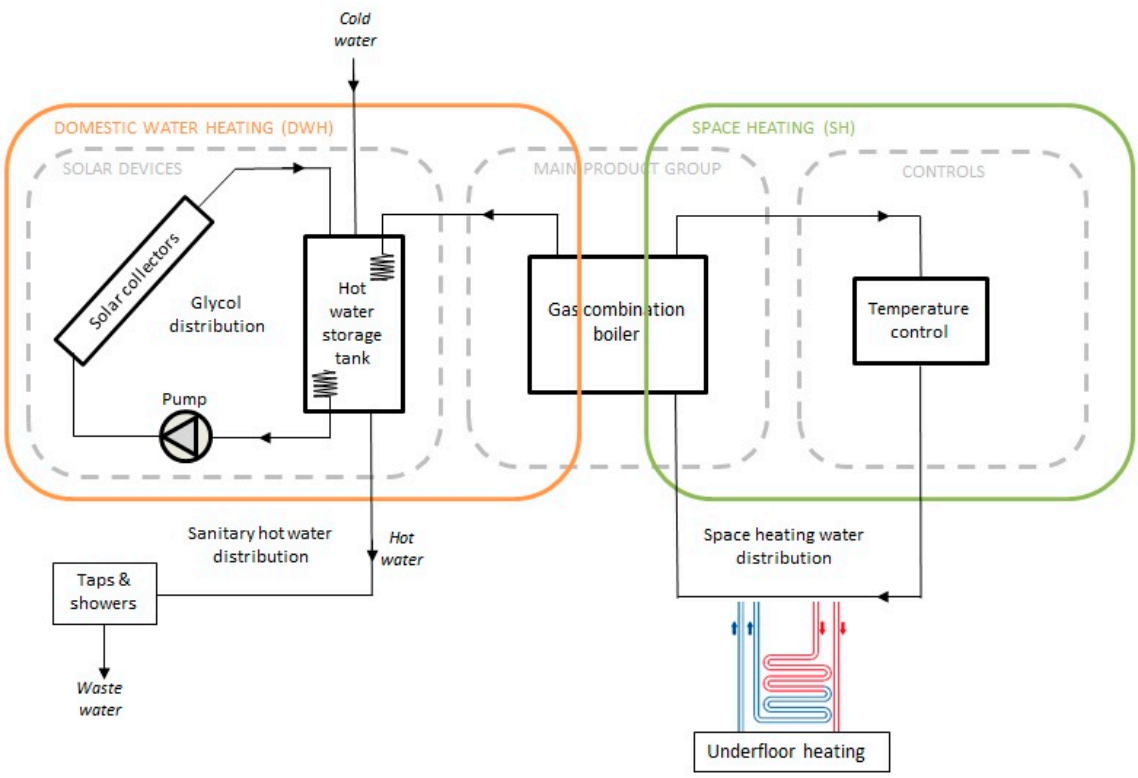

Figure 5. Heating systems considered in the case study.

The DHW system consists of the water heater, a solar collector with a glycol pump, a sanitary water pipe network, a storage tank with two coils, three taps and one shower. The SH system includes mainly the boiler, the distribution components, the underfloor heating and the temperature controls.

Table 3 shows the EU regulations that affect the products and packages described in the case study. The package and label are composed of a combination heater with solar devices and a temperature control, according to Regulation 811/2013. Two different calculation schemes are used to calculate the water heating energy efficiency and the space heating energy efficiency of each of the functions of the heating systems (Table 3). However, because the house had been completely refurbished in 2012, that is, before the regulation entered into force (September 2015), the labelling of the package was not available when the installation took place. In this section, the package energy efficiency is calculated and the energy class set for both DHW and SH systems (in Table 3) using data available from the installed products.

Table 3. Energy label regulations affecting the case study.

Label	Product/Package	Efficiency Type	EU Regulation (Calculation Schemes)
Product label	Gas combination boiler	Water heating energy efficiency Space heating energy efficiency	Regulation 811/2013 [10]
	Storage tank	Standing losses	Regulation 812/2013 [9]
Package label	DHW system: gas combination boiler plus solar devices (solar collector, solar storage tank and solar pump)	Water heating energy efficiency	Regulation 811/2013 *Annex 4, Figure 5* [10]
	Space heating system: gas combination boiler plus temperature control	Space heating energy efficiency	Regulation 811/2013 *Annex 4, Figure 1* [17]

Table 4 shows the technical parameters, provided by manufacturers of the devices, needed to calculate the package water heating energy efficiency of the DHW system and the package space heating energy efficiency of the SH system in the case study.

Table 4. Technical parameters of the heating systems in the case study.

System	Product Category	Components	Parameter	Value	Units
DHW system	Solar devices	Solar collector (flat plate)	Collector aperture area	2.06	m^2
			Zero loss collector efficiency	75.2	%
			First-order heat loss collector efficiency	3.55	$W/m^2 \cdot K$
			Second-order heat loss collector efficiency	0.018	$W/m^2 \cdot K$
			Incidence angle modifier	0.94	–
		Solar storage tank	Storage volume	160	l
			Backup storage volume	80	l
			Thermal dispersion	1.52	W/K
			Standing losses	69	W
		Solar pump	Power consumption	28	W
	Main product	Gas boiler	Water heating energy efficiency	74.4	%
			Space heating energy efficiency	92	%
SH system	Controls	Temperature controls	Type V: % contribution of the space heating energy efficiency of the package [21]	3	%

According to Regulation 811/2013 [10], combination heaters have two different energy efficiencies, one for each of their functions. The manufacturer declared that the combination boiler in this case had an energy label A for the DHW and space heating systems. The water heating function of the boiler had a load profile M, according to tapping patterns described in Regulation 811/2013 [10] for combination water heaters (relevant for Q_{ref}). The storage tank had an energy label C, according to Regulation 811/2013 [10].

According to Regulation 811/2013, for the calculation of the water heating energy efficiency, additional intermediate parameters are needed (Table 5). The Q_{nonsol} and Q_{aux} have been calculated with SOLCAL [22]. SOLCAL is free software available online, which is recommended by European Commission [23] for calculating the non-solar energy needed in the package and includes several technical parameters for the solar devices.

Table 5. Parameters needed for the calculation of the water heating energy efficiency in the case study.

Parameters for DHW System	Value	Units	Source/Calculation
Q_{ref} (M profile)	5.845	kWh/year	Regulation 811/2013 (*Annex VII, Table 15*)
Q_{nonsol}	1050	kWh/year	SOLCAL calculation [20]
Q_{aux}	56	kWh/year	SOLCAL calculation [20]
I′ = water heating energy efficiency of the boiler	74.4	%	Boiler manufacturer (Regulation 811/2013)
$II' = 220 \times Q_{ref}/Q_{nonsol}$	1.225	–	Formula from Regulation 811/2013 (*Annex IV, Section 6b*)
$III' = (Q_{aux} \times 2.5)/(220 \times Q_{ref})$	0.109	–	Formula from Regulation 811/2013 (*Annex IV, 6b*)
Solar contribution = $(1.1 \times I' - 10\%) \times II' - III' - I'$	2.69	%	Formula from Regulation 811/2013 (*Figure 5*)

Table 6 shows the results for the water heating energy efficiency and class of the DHW system and the seasonal space heating energy efficiency and class of the SH system in the case study, when implementing the calculation scheme from *Figure 5* of Regulation 811/2013.

Table 6. Package energy efficiencies and class for the case study.

Type of Package Energy Efficiency			Package Energy Class [10]
Water heating energy efficiency	For an average climate, this is I′ plus solar contribution	77.1%	A
	For a colder climate, this is the value for an average climate minus 0.2 × solar contribution	76.6%	–
	For a warmer climate, this is the value for average climate plus 0.4 × solar contribution	78.2%	–
Space heating energy efficiency	Seasonal space heating energy efficiency of boiler plus the package parameter of the temperature control	95%	A

Figure 6 shows the resulting package label for the case study. The main product group (the combination boiler) and the additional components (solar collector, storage tank, temperature control and supplementary heater) are shown on the left and the efficiency classes for each of the functions are shown on the right of the label.

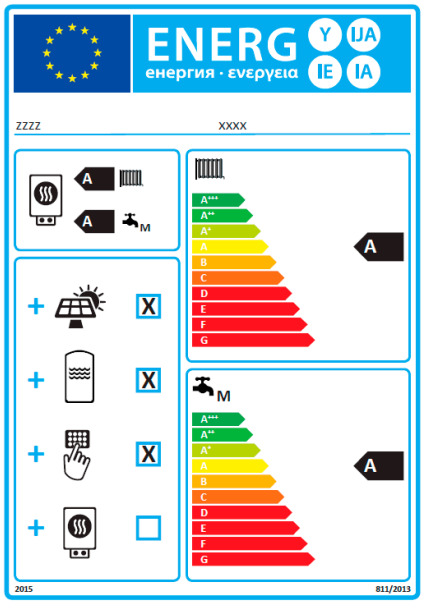

Figure 6. Label for the package of combination heater, temperature control and solar device in the case study.

3.1. Analysis of the Improvement Potential of the Package When Upgrading the Products

This section shows how data from product policies could be used by building designers to produce better design alternatives (DAs). Building engineers, who are responsible for heating system design, could make different product choices based on the different performance levels of the products. Further analysis of the case study reveals how upgrading each product (which can be proposed by building designers) can affect the package energy efficiency.

Therefore, the performance levels of each product have been assessed. Firstly, the influence of each individual product (without modifying the other products) on the potential improvement of the packages is analysed. Secondly, different DAs are presented according to the combination of the improved performance levels of one, two and three products.

In the DHW system, the heater already has the highest energy class, class A, but its water heating energy efficiency could be increased to 100% by choosing a better boiler [10]. In theory, the heater could achieve energy classes that are higher than class A, but only in packages of boilers with solar devices and temperature controls [10]. However, in this analysis, we consider the improvement of only one component (considering the boiler and solar devices separately) to calculate the package efficiency;

therefore, we disregard energy classes higher than class A. Therefore, two heaters are considered (with efficiencies of 74.4% and 100%). One solar collector (2.06 m^2), two collectors (4.12 m^2) and three collectors (6.24 m^2) with the same characteristics are considered. The highest possible energy class of the solar storage tank is class A^+ with no standing losses (SL = 0 W); however, in this analysis, we consider only tanks with minimum standing losses (SL) of 15 W, which is closer to reality. Therefore, five storage tanks are considered, one for each performance level based on their standing losses; C of the case study (SL = 69 W), C maximum (SL = 58 W), B (SL = 41 W), A (SL = 30 W) and A^+ (SL = 15 W). In this analysis, the solar collectors and the solar storage tank have been considered as two separate products to distinguish their individual influences, although Regulation 811/2013 considers them together in calculating the solar contribution. Figure 7 shows the influence of each product on the improvement of the overall water heating energy efficiency of the package. Figure 8 presents the package water heating energy efficiency values of the combinations of the performance levels of one, two and three products, showing the easiest and most realistic DAs.

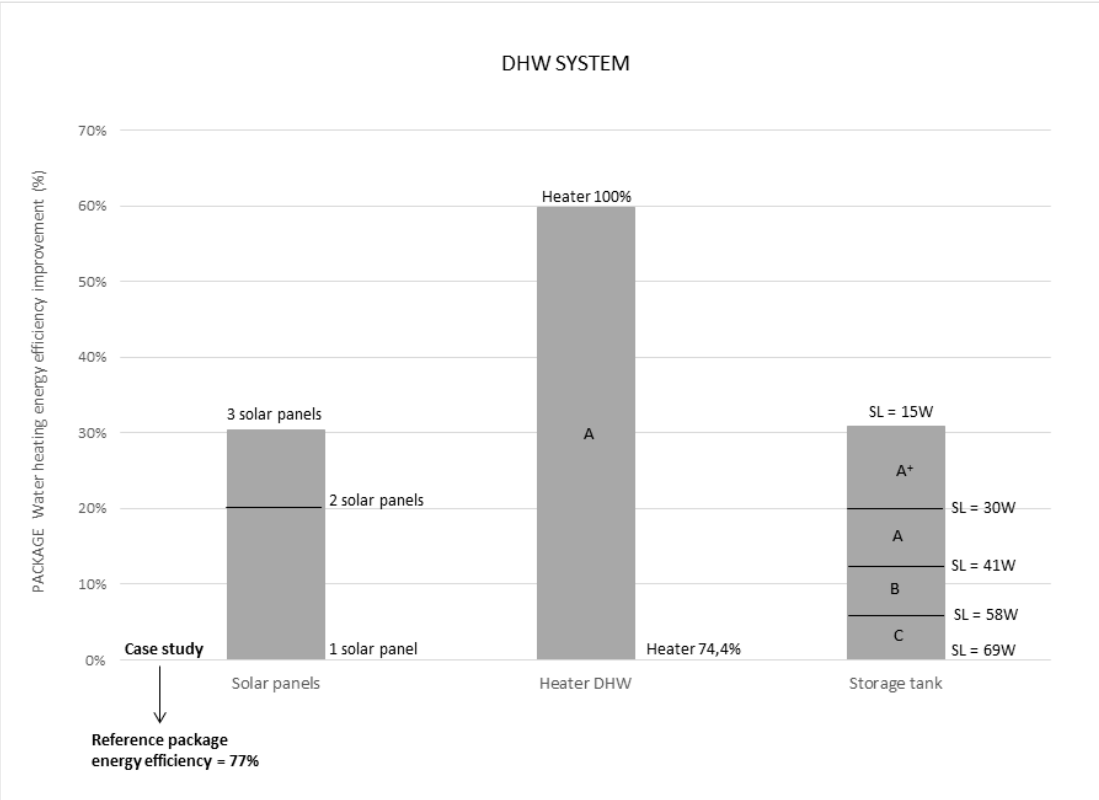

Figure 7. Contribution of individual products to the water heating energy efficiency improvement of the package.

The case study gave a package water heating energy efficiency of 77% (Table 6), which is the reference line. The heater or boiler alone had the highest improvement potential (60%) for the package, which could reach 137% (DA1 in Figure 8) of package energy efficiency. A storage tank with an energy class A^+ (SL = 15 W) could increase the package energy efficiency to 108%. Storage tanks with energy class C maximum (SL = 58 W) would improve the package energy efficiency to 82% (DA2 in Figure 8). Installing three solar collectors (6.24 m^2) would improve the package energy efficiency by 30% (107% package energy efficiency). Using two solar collectors instead of one would increase the energy efficiency of the package to 97% (D2 in Figure 8).

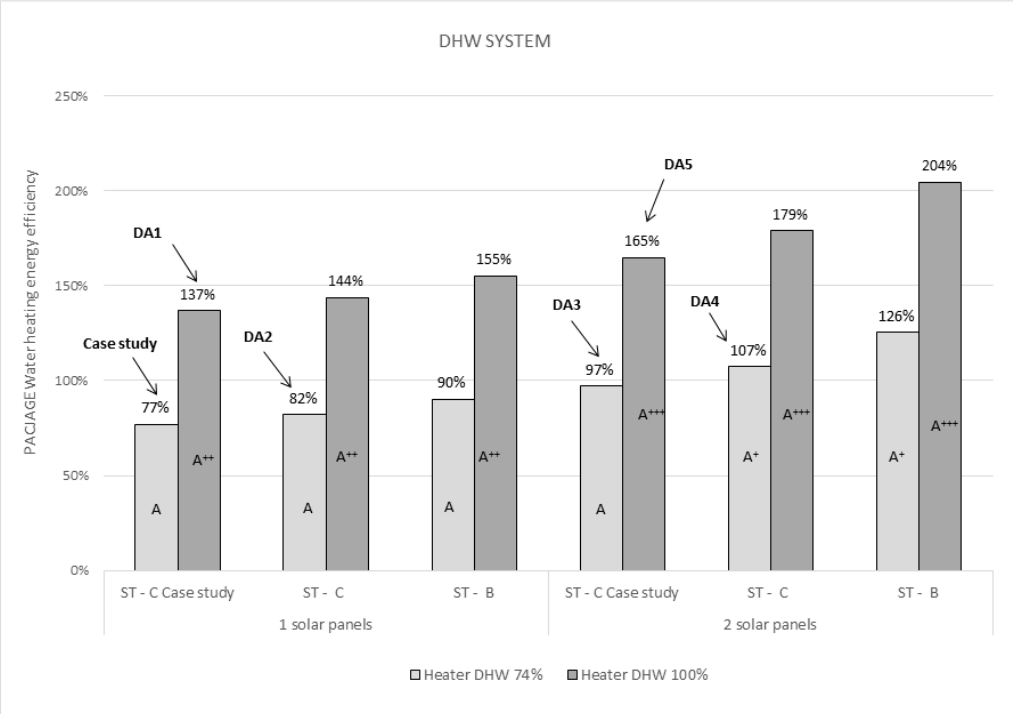

Figure 8. Combined options to improve the water heating energy efficiency of the package.

However, storage tanks of class A or above would require innovative solution technologies, such as evacuated systems or aerogels, and the installation of three solar collectors might not be justified in such a small house (60 m^2). Therefore, to simplify the figures, the unrealistic storage classes A and A^+ and the option of three solar collectors are not assessed in the analysis of better DAs (Figure 8).

Figure 8 shows results of combining the improvements resulting from different package products (the heater, the storage tank and the solar collectors) under the same assumptions as in Figure 7 to select a new design that could upgrade the package water heating energy class to better than class A. Five DAs are proposed when upgrading one product or the combination of two products in the system. Firstly, to achieve a package energy class A^+, a storage tank in energy class C with SL = 58 W and two solar collectors would have to be used (DA4). Secondly, a package energy class A^{++} could be achieved using a heater with 100% water heating energy efficiency (DA1). The highest package energy class A^{+++} could be achieved using two solar collectors or panels and a heater with 100% water heating energy efficiency (DA5).

Regarding the seasonal space heating energy efficiency of the package, Figure 9 shows the results of the analysis for the system when upgrading the performance of either the heater or the temperature controls. Two heaters have been considered, with 92% and 98% space heating energy efficiencies. The former is the one used in the current design of the case study and the latter corresponds to an EU Ecolabel [24]. Three temperature control classes have been considered: control class V (the one used in the case study, which is a modulating room thermostat for use with modulating heaters), class VI (a weather compensator and room sensor for use with modulating heaters) and class VIII (a multi-sensor room temperature control for use with modulating heaters), which contribute 3%, 4% and 5%, respectively, to the seasonal space heating energy efficiency of packages (temperature control class VII is not included in this analysis, since the heater in the case study is a modulating boiler and this class is for use with on/off output heaters [21]).

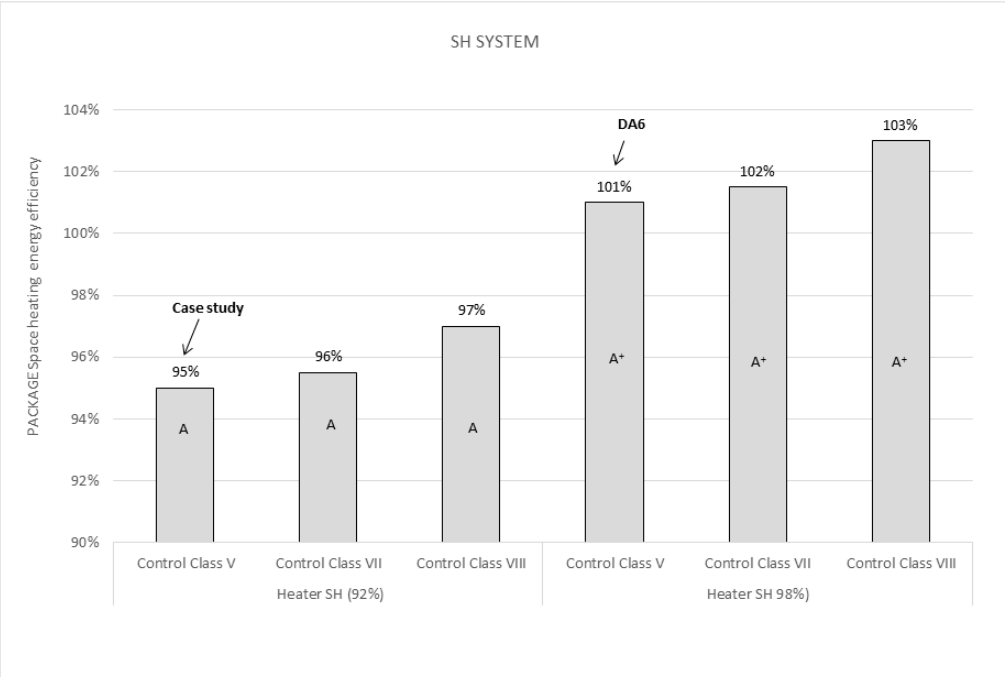

Figure 9. The Influence of the heater and the controls on the space heating system.

The heater or boiler has a greater influence on the package efficiency than the temperature controls (Figure 9). By improving the space heating energy efficiency of the heater from 92% to 98%, the package would increase its efficiency from 95% (package energy class A) to 101% (DA6; package energy class A^+). Improving the temperature controls to those in the highest class increases the package efficiency only to 97%. However, controls in class VIII, which use multiple sensors, might not be appropriate for a 60 m^2 dwelling.

Table 7 presents the summary of results for the different DAs proposed in this analysis. In principle, the easiest way to improve the energy efficiency of the package would be to modify only one product (DA1, DA2, DA3 and DA6). However, DA2 and DA3 do not improve the package energy class, which remains class A. DA4 and DA5 require the modification of two products, although they achieve a higher package energy class (classes A^+ and A^{++}). The space heating energy efficiency has very limited potential for improvement. We propose only DA6, which requires the space heating energy efficiency of the boiler to be upgraded and results in the package achieving slightly higher energy efficiency (101%) and becoming class A^+.

Table 7. Summary of the results for the package-improving potential of upgrading the products.

System	DAs—DESIGN ALTERNATIVES	Package Energy Efficiency (%)	Package Energy Class
DHW	Case study	77	A
	DA1	137	A^{++}
	DA2	82	A
	DA3	97	A
	DA4	107	A^+
	DA5	165	A^{+++}
Space heating	Case study	95	A
	DA6	101	A^+

4. Discussion

4.1. Lessons Learnt from the Case Study from a Design Perspective

The package concept was implemented using a real case study, which includes a water heating system and a space heating system (Section 3). In accordance with Regulation EC 811/2013 [10], two different energy efficiencies were delivered: the water heating energy efficiency (based on the heater and the solar devices, which include the solar collectors, the storage tank and the solar pump) and the space heating energy efficiency (based on the heater, as before, and the temperature control). The package water heating energy efficiency was 77.1% (class A, see Table 6) and the package space heating energy efficiency was 95% (class A, see Table 6). Further analyses were carried out in this case study and DAs (including improved designs) were analysed (see Section 3.1). This design perspective showed that, thanks to the package concept, it is possible to identify the improvement potential of the system easily when considering several potential upgrades of products to higher classes. Several alternatives (improving the boiler, adding a new solar panel, changing the storage tank or a combination of these solutions) for reaching a given objective are possible, and data for the assessment of these alternatives are available from the package energy label declaration. For instance, changing the storage tank to one with a C energy label and adding another solar panel would increase the package energy efficiency from 77% to 107% and the package energy class from A to A^+ (see Table 7). Then, this analysis shows the usefulness of using data from product policies to support design decisions.

However, it was also shown that the package concept is not a complete approach because it does not consider all the products contributing to the performance of the system, such as the heat distribution system and/or the delivery components (e.g., the taps and showers or the underfloor heating), which could have a significant influence on the losses/savings of the overall system (see e.g., Section 3 and Figure 5).

The case study (Section 3) demonstrates that product policies could have added value in design choices. The use of EU product policy data has the advantage that it is based on homogeneous and agreed calculation methods, which makes fair comparisons of products possible [25]. These figures are available from either the regulations themselves or the manufacturers' technical documentation. In addition, the rapid development of the technology of energy-consuming products means that these regulations must be updated regularly; therefore, designers have information on the products that are available in the current market. Therefore, although the calculation methods applied in product policies might have some limitations in the accuracy of the performance figures they provide, they could be sufficient for building professionals who need data that are available and do not have to be very precise in the early stages of design.

4.2. Limitations and Perspectives of the Package Concept

The method of calculating package energy efficiency by adding different product performances (heater, solar devices and temperature controls) might be not accurate, since it does not represent the real interactions of these products. However, it is the best available in the policy context, since it has been agreed among stakeholders (e.g., industry, government, consumers organisations) and allows the comparison of different equivalent packages.

In the future, more accurate energy efficiency calculations could be made available, by two means. One is the development of benchmarks for packages. The energy benchmarking of systems engineering involves comparing the energy performance of a system with a common metric that represents the optimal performance of a reference system [26]; this, is not available yet for heating packages. Benchmarking is a key policy model to improve building energy efficiency and retrofitting [27]. Once the energy labels of packages are well established and documented (the regulation came into force in September 2015), the benchmarking of packages of heating systems will probably be easier and policy makers will be able to set efficiency targets for these packages. Alternatively, considering that the real efficiency of a system is not the sum of the efficiencies of its components, harmonised

calculation methods should be developed by standardisation organisations so that the calculated efficiency of the system can be closer to reality. Design teams could also benefit from such standardised methods in the future when looking for design alternatives.

Another limitation is that the package is just a sub-system and not the whole system; heat distribution or delivery components, which are also parts of heating systems, are not included. However, the modular approach of the package concept could allow the inclusion of new additional components, which have not yet been considered. In addition, the package concept does not include other relevant criteria. The schemes set in Figures of Annex 4 of Regulations 811/2013 [10], 812/2013 [9] and 1187/2015 [17], which detail each package energy efficiency calculation methods, include a footnote describing some limitations on the results for the package energy efficiency. For example, it is stated (see footnote in Figure 4) that the efficiency of the package might be influenced by additional factors, such as distribution losses and the dimensioning of products according to the size and characteristics of the building. In addition, neither climate conditions nor losses due to the building characteristics, which can have a significant influence on the energy services demand of the dwelling, are considered. However, the inclusion of distribution and delivery components and other relevant criteria in the systems may fall under the competence of the EPBD.

4.3. Links between Building-Related Product Policies and Energy Performance of Buildings Directive

The modular approach of Ecodesign and Energy Labelling Directives packages is different from but complementary to the system approach under the EPBD, in which the entire installation and the building heat losses are considered, although the heat demand and the required heating capacity are also relevant [19]. Both policies complement each other to realise a large energy-saving potential. The Ecodesign and Energy Label Directives guarantee good-quality individual heating products, including products used for retrofitting, while the EPBD addresses the performance of the whole building and is applicable mainly to new buildings. The introduction of the package label could be seen as an attempt to bridge the gap between the two policies. However, the picture is still fragmented. The links between products, systems and buildings are weak and the Ecodesign/Energy Labelling product groups do not necessarily cover all the essential products in the system [28].

The EPBD considers the building itself as the system boundary for the purpose of analysis (Figure 10) and includes its particular global context (e.g., external climatic conditions, building characteristics, envelope, energy services demand). Therefore, "all the system" in Figure 10 means not only all the products of the system but also this global context. It also defines the "technical building system" as the technical equipment for the space heating, cooling, ventilation, hot water, lighting or a combination thereof, for a building or building unit (Figure 10). Member States, through the EPBD, should set minimum energy performance requirements for technical building systems (including hot water and space heating systems). Ecodesign measures for heaters and related products provide harmonised minimum efficiency requirements (Article 8 of the EPBD [4] links the EPBD with Ecodesign and Energy Labelling Directives').

The technical building system (from the EPBD) and the system approach (from product policies) have a common level of analysis at the technical building system level, for instance in the "space heating system", understood as the group of products and components needed to deliver space heating in a dwelling. However, despite their obvious relationship, the EPBD and building-related product policies work in parallel since they have different definitions for the term "system". Nowadays, they are independent policies and address different situations in which a product may be purchased or installed (although the EPBD sets requirements for buildings' energy performance in the case of new buildings or major renovations and will thereby also affect the choice of the heating system, it does not cover cases where only a boiler is retrofitted in an old building. In these cases, the Ecodesign and Energy Labelling Directives support the choice of an efficient product). The EPBD has a top-down approach, while the building-related product policies have a bottom-up approach. These policies should be better aligned, in particular by ensuring the coherence of their scope. For instance, the technical building

system should be equivalent to the system approach of product policies. In this way, it would be possible to bring macro-scale (e.g., the EPBD) and micro-scale (e.g., EU product policies) policies closer together in the building sector, so that consistent top-down and bottom-up energy-saving targets can be implemented.

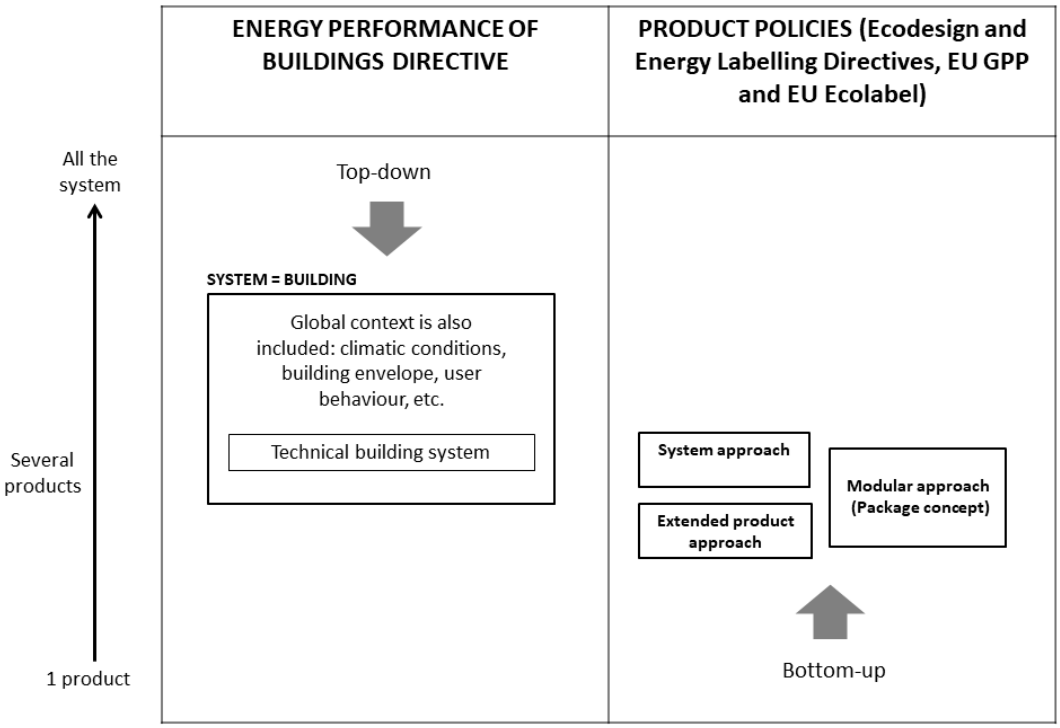

Figure 10. Link between the EPBD and building-related product policies.

5. Conclusions

This paper presents an analysis of some EU product policies, in particular examining how they address the energy efficiency of complex systems that contain several products. A particular focus is on the package concept, which is a modular approach between the extended product and the system approaches (Figure 1). The package concept has so far been applied only to heating systems, in particular through Regulations 811/2013, 812/2013 and 1187/2015 (Section 2). The calculation method of the package energy efficiency is straightforward to apply; therefore, it can be implemented easily by manufacturers and dealers and understood easily by consumers. It is more flexible than the formulae used in the extended product or system approaches because it allows new components' efficiencies to be added easily to the efficiency of the main product group. Then, although design of efficient heating systems is complex and require advanced modelling skills, designers of systems could benefit greatly for having access to such simple assessment methods at early stage of the design. However, it has some limitations regarding missing components that are part of heating systems (e.g., distribution and delivery components) and regarding insufficient consideration of the interactions between components. The real efficiency of a system is not the simple sum of the efficiencies of its components. In addition, dimensioning of products according to the size and characteristics of the building and the geographical and climatic conditions are not considered in the analysis of the package energy efficiency.

The package concept was implemented in a real case study that includes a water heating solar system and a space heating system (Section 3). The package energy efficiency and class (see results from Table 6), and label (Figure 6) was calculated using a step-by-step process for these systems. In addition, based on the case study, further package analyses relevant for designers were carried out on the potential to improve the packages if the products are upgraded. In particular, six design

alternatives are presented in Section 3.1 (see Figures 7 and 8) in which the package energy efficiency and/or class are improved when the boiler, the storage tank are upgraded or when more solar panels are added. These analyses showed the potential of using product policies to support technical decisions in the system design phase. This brings building engineers and regulators closer together regarding the use of more consistent data on energy performance.

The package concept of heating systems and the EPBD are complementary, but the latter considers the building itself as the system for the purpose of analysis (Figure 10). It is still an open question where systems based on modular approaches of building-related product policies end and where the technical building systems defined in the EPBD begin. In this regard, a common policy development would be needed to address equivalent terminology and the boundaries of systems.

To improve the calculation method of the energy efficiency of packages, we propose the use of benchmarks and the further development of standardisation methods. In addition better alignment of building-related product policies with EPBD would lead to overcome limitations such as better considering additional components, the building characteristics and envelope, or the climate conditions. In addition, further research is needed to develop calculation methods that are better aligned to each of these policies applied to the energy efficiency of systems.

Author Contributions: Maria Calero-Pastor carried out all of the research work (design of research, data collection, analysis and interpretation of the results) and was the main author of the paper. Fabrice Mathieux contributed to the design of the research, the structure of the paper, the creation of figures and the discussion of results. His contribution concerned mainly the sustainable product policies perspective. He contributed mainly to Section 1 (introduction), Section 2 (analysis of the package concept) and Section 4 (discussion). Daniel Brissaud contributed to the design of the research, the structure of the paper and the discussion of results. He contributed mainly to Section 1 (introduction) and Section 2 (analysis of the package concept). As an expert in engineering systems, his main contribution concerned efficient heating systems design. Luca Castellazzi contributed to the review of the whole paper as an expert in energy efficiency and energy policies. His writing contribution was particularly relevant in Section 2, Section 3 (the application of the package concept to a real case study) and Section 4 (discussion), in particular to the links between the building-related product policies and the EPBD.

Conflicts of Interest: The authors declare no conflict of interest.

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6.3 Further discussion: the package label vs. the method proposed

The fact of implementing the package label (in the paper) to the same case study of this manuscript (section 5) has allowed contrasting both results.

Firstly, concerning the components weight in the package water heating energy efficiency, the heater (water heating function) is the component with higher improvement potential in terms of package energy efficiency (Figure 7 of the paper). This is due to the fact that the package label gives great importance to the heat generator which is the component which directly consumes the energy (the package label is a sum of the efficiency of the generator plus additional bonus from the use of solar/saving devices). In contrast, implementing the method to the case study (section 5), the water heating function of the boiler is the third component with the highest improvement potential (on energy savings) (Figure 13 of the manuscript). In the method (section 4) all the system components have the same weight when calculating the system energy performance.

In terms of package energy efficiency (Figure 7 of the paper), the use of more solar panels has more importance regarding improvement potential in the package than applying the method (section 5.1.1.3). Renewable energy sources are rewarded by product policies in order to promote the use of this type of technology. In section 5.1.1.1, the solar contribution has been assessed with SEAS solare, software which takes into account the solar irradiation in each specific region of Italy, the orientation of the building, etc. so we could say that results are more accurate than those in the package label in which the global context is not considered.

On the other hand, taps and showers are excluded from the analysis of the package label. Section 5.1.1.3 shows the great energy saving potential of taps and showers. In addition, these components are much easier to be replaced and cheaper than the rest of the components (section 5.1.3). Therefore, the exclusion of taps and showers in the package label is making to miss an important aspect of the system improvement potential. The underfloor heating and distribution are neither considered in the package label; however, these were assessed as no relevant to be improved at step 3 of the method.

The package energy efficiency is calculated by summing the performance of different product parameters. The energy flows from one component to the next are not addressed in the package approach, as they actually are in the method proposed in this manuscript. In addition to this package (heater, solar panel and storage tank), distribution components, the taps of showers and the underfloor heating should be also included, since they are part of the system. The method proposed in section 4 includes the losses of all the components of the heating system (distribution and delivery components) and the global context (climatic conditions, building characteristics, and user behaviour). Thus, the method proposed (section 4) is more complete than the EU package concept in terms of considering a more system approach.

When analysing the improvement potential of packages in the case study (Figure 8 and 9 of the paper), similar overall conclusions are achieved than with the method proposed (Figure 16 of the manuscript). The boiler and the storage tank have great improvement potential on the package label (paper) and applying the method (manuscript, section 5). The fact that similar conclusions can be drawn from results from the EU package concept (in the paper) and the method proposed (in section 5) shows that although the limitations of the package concept (e.g. missing components and climate conditions, among others), the latter still gives consistent outcomes. An advantage of the package concept in contrast with the method proposed is that its application is easier and more straightforward.

In summary, the design method proposed in section 4 of this manuscript tries to go beyond the current EU package approach since it takes into account the specific global context and the component configuration, including every element, and is therefore, more realistic in terms of the geographical conditions, building envelope and heating system (it includes the energy demand and system energy losses). The energy balance applied in the method is more accurate than the simple addition of parameters applied in the EU package regulations and thus, it gives a more precise performance figure. In addition, the method proposed allows changes in the configuration of the system in a more realistic way than the EU concept package does.

6.4 Conclusion

This section has been useful for checking how engineering systems (section 2.2) are currently addressed in the policy framework. The evolution of the system approach in building-related product policies has been done from the bottom-up since the initial point are ‘products’. On the other hand, the Energy Performance of Buildings Directive does it the opposite through the top-down approach, since the starting point is the ‘building context’. It is not an easy task neither to establish limits nor setting commonalities or matching points between these two approaches. This makes some system components to be in the limbo of both policies and to have the system perspective fragmented. In conclusion, greater efforts are needed to better align the building-related product policies with the EPBD. With this regard, the method proposed in section 4 covers all products and sub-systems, since both the top-down and the bottom-up approaches are implemented and it could hence be a good way to bridge those complementary approaches.

The case study of the paper implements the package label according to Regulation 811/2013 and shows how data from product policies can be useful in a design context. Results show that the package concept, although less comprehensive and precise, can also support decisions made in the building design phase and in particular, to support the choice of appropriate components based on estimation of system performances.

The research done in this section shows that, whatever the method is to be used during the design process (i.e. detailed or simplified), it is important that building designers adopt approaches aligned with regulations, regarding the use of more consistent data on energy performance in order to achieve greater energy savings in the building sector.

7. DISCUSSION, CONCLUSIONS AND PERSPECTIVES

7.1 Conclusions

This dissertation presents a simplified design method useful for building engineers which aims at providing good design alternatives of efficient heating systems, based on the combination of products performance levels taken from European sustainable product policies (Ecodesign and Energy Labelling Directives, EU Green Public Procurement and EU Ecolabel). This work contributes to increase the efficiency of heating systems and to reduce the energy consumption in buildings. In summary, the problems which carry the energy use (e.g. pollution, illnesses, fuel dependency, etc.) could be mitigated.

In particular, some methodological challenges of environmental assessments of systems at the design step are explored. Method requirements (section 3) were identified from the review of the scientific literature on engineering systems, especially on HVAC systems, and from the analysis of product policies (section 2). The aim was to propose a design method for supporting the design of good performing heating systems using data from EU product policies.

For analysing engineering systems, both top-down (from systems to products) and bottom-up (from products to systems) approaches can be applied. However, the top-down approach is more complex and thus, less implemented. The scientific literature on environmental assessments on HVAC systems uses the top-down approach and holistic environmental assessments such as LCA. The use phase is always considered, being the energy consumption the most important environmental aspect and sometimes it includes the manufacturing phase. In contrast, the review on product policies (Ecodesign and Energy Labelling Directives, the GPP and the EU Ecolabel) on HVAC systems shows that these regulations usually apply the bottom-up (or extended product) approach to include additional products, part of the system, that influence the overall performance. The system approach, i.e. including all the influencing components is not widely applied in product policies. Product policies focus on environmental performances during the use phase, including energy efficiency, although other aspects can also be considered (e.g. air emissions, sound levels or other technical requirements).

Considering the voids in the scientific and technical literature, the method presented in this manuscript (section 4) proposes firstly, a system modelling with a top-down approach so that system aspects (geographical conditions, building characteristics, etc.) are regarded. Secondly, the system energy performance is calculated from a bottom-up approach so that, from the performance of the products and sub-systems composing the system.

The method provides three new aspects that are not yet covered by the literature:

1. It allows the assessment of heating systems grounded on well-known and proven labelling schemes such as EU product policies, which are available at the early design stage and implemented by all manufacturers.

Data from EU product policies have the advantage of being based on homogeneous calculation methods and ratings for a particular product group. This is useful since the performance of components comes from an agreed evaluation process that makes it easier to compare products. These figures are easily accessible at the design step, available either from the regulations themselves or from manufacturers' technical documentation. In addition, as these product policies are continuously reviewed in order to adapt to market dynamics, performance calculation methods and thresholds are regularly updated. When EU product policy data are not available, the method is flexible enough to allow designers to decide on which other calculation tool to use. As alternatives to EU product policy data, rules of thumb and professional software such as computational simulation tools can be used to assess product performance.

2. It supports design activities at system level, providing informed decision-making on multiple design solutions based on different configurations of products with performance levels currently available on the market.

   Designers, according to EU product policies, can study the performance levels (i.e. energy classes) of a component before choosing the product, available in the market, to be installed. Then, the method enables the assessment of solutions, the comparison of alternatives and optimisation of the energy performance of the system at various stages of the design process, especially in the early stages. It also helps guiding design activities towards energy-saving targets.

3. It allows to assessing how good a heating system is by setting worst, benchmark and best systems. Thus, the improving potential can be easily identified. This is not a novelty for instance at product or building level, but it is at the HVAC installation level.

   The method is based in energy benchmarking of systems in order to ensure that the heating system is a good performing design. Benchmarking is used in product policies by giving relative performance information based on the average market characteristics and setting thresholds. Then, to be able to design a system according to certain energy efficiency target is a preliminary stage in the benchmarking of the energy efficiency of heating systems for regulating purposes. The work presented in this dissertation could be useful for formulating product policies thus, helping better set up a product rating scheme for heating systems and other HVAC systems.

Besides the method, a calculation tool is proposed (section 4.3). The calculation tool allows assessing the system energy performance of the initial, best, worse, benchmark and additional improved design alternatives. It is focused on four parameters: energy demand, energy losses, non-renewable energy consumption and low-emission energy efficiency. These parameters are needed not only to assess but also to compare such systems with the initial system, with the aim of minimising the energy consumption at system level.

The method was applied to a real-life case study (section 5) consisting in the re-design of two heating systems (a solar sanitary hot water system and a space heating system). Section 5 shows how the steps of the method are applied, which data is used and which results are produced. Results show the quantification of the influence of the different performance levels of individual components currently available on the market in the overall system. The proposed method helps designers to study and compare various alternatives (worst, benchmark and best systems and up to 9 design options), combining different product performance levels and simulating their system performance. This could be done either through simple modifications of the current devices or through the substitution by a better device.

In addition, an extended analysis of the case study verified that the method works properly when variables which in principle are fixed in the original method, are modified. The change of location (from north to south Italy), the energy demand (doubling the number of users) and the technology (substituting the boiler by a heat pump) were assessed.

The last part of the dissertation (section 6) analyses the evolution of the different approaches (product, extended product and system) of EU product policies from a design point of view. This is presented in a scientific paper recently published in Energies Journal. In particular, the package concept set in Regulation 811/2013 (EC, 2013e) is studied and implemented in the same previous case study (that from section 5). It is shown that the package concept can also support decisions made in the building design phase especially in the choice of appropriate components based on estimation of system performances. Although the limitations of the package concept (e.g. missing components and climate conditions, rough calculation, etc.), some coincident conclusions can be drawn from the EU package concept than from the method proposed in this manuscript (section 4), which shows the validity of the former. On the other hand, the method proposed is more complete, accurate and flexible, and hence has the capacity to better support design activities of specific heating systems. In addition, the paper analyses the link of building-related product policies with the Energy Performance of Buildings Directive, and it is concluded that they should be somehow better aligned.

The main contribution of this research is then, to the engineering design field, especially at the early stage of design. The method proposed represents a step forward on how to address better the system approach in environmental assessments, in particular in energy performance, and how this could be applied to ecodesign of product's systems. However, it has also a potential use in policy, for instance for including more system aspects in product policies and/or to align better both building-related product policies with EPBD. Therefore, this work improves the task of building designers and regulators to easier achieve common and equivalent energy efficiency objectives.

7.2 Limitations and perspectives

Regarding the procedure of the method, as shown in the case study (section 5.1), the global context, the user behaviour and the building envelope losses are initially assessed at step 1 and remain constant throughout the next assessment steps. The addition of new components would also need a revision or a redefinition of step 1, in particular of the system modelling. However, as shown in section 5.2, the method is flexible enough to restart the method redefining parameters at step 1, if the global context or the system modelling changes. The calculation tool facilitates this, reassessing easily the energy flows. However, for new designs, it could be useful to further analyse and compare installations with very different technology and/or installations. Obviously, the choice of more efficient technology, especially the heat generator, would lead easier to more efficient systems (e.g. replacement of a boiler by a heat pump, see an example in 5.2.3). For new designs, some modification/additions would be probably necessary at Step 3 of the method so that to include different assessments of the influence of relevant products on the overall system on two main alternatives (e.g. the water-based heating system run with a furnace against an air-based one run with a heat pump).

The calculation methods on the energy performance of products applied in product policies might have also some limitations in the accuracy of the values they provide, and nowadays face the additional challenge of dealing with product systems. However, the method proposed in section 4 is based on simplified methods which could be useful for decision making at the early steps of design, and thus, it is secondary if it does not provide very accurate system performance figures.

The proposed method (section 4) is valid only if the behaviour of each element is quasi-independent of the others; energy balances done in the method are simple aggregation functions. In reality, the behaviour of the system is not a simple combination of the behaviours of its elements. In principle, in the method, the interdependencies among elements are not considered at calculating the system energy performance. However, an approximation in results is usually enough at the design step and dependencies and synergies could be studied later in the development process or once the technology is chosen or installed.

Regarding the calculation tool, fluid thermodynamics is not directly applied to the energy performance analysis of such systems. This would depend on the detailed level of building/HVAC simulation tool chosen to aid the method proposed. Therefore, certain assumptions and simplifications depend more on the tool chosen, than in those made by the designer during the application of the method. On the other hand, since other simple tools could be used (e.g. rules of thumbs), the accuracy of the system energy performance could be less accurate and assumption-dependent.

Another limitation of the method is that it is restricted to energy aspects during the use phase. The Roadmap to a Resource Efficient Europe (EC, 2011c) mentions that the life-cycle approach should be more widely applied in buildings, which means that

other phases different from the use phase should be included (e.g. building products manufacturing, construction or demolition phases) as well as other environmental aspects than energy consumption (e.g. pollutants and waste emissions) in the environmental assessment of buildings. With this regard, the EC has recently developed Level(s), a common EU framework of core indicators for the sustainability of office and residential buildings for measuring the environmental performance of buildings along their life cycle (EC, 2017). Indeed the literature review of HVAC systems (section 2.4) shows that there are some studies which include the manufacturing phase (e.g. embodied impacts of (Yang et al., 2008)). In addition, the EU Circular Economy action plan (EC, 2015a) claims for measures to improve consumer information not only on energy efficiency of products but also on the raw materials used in their production and the possibilities for recycling at the end of their life. Thus, further research could focus on developing a similar calculation tool for resource efficiency aspects for the system and on adapting the method for this purpose. Resource efficiency parameters for HVAC products could include reparability, upgradability, durability and recyclability. For instance, a good source of inspiration could be the work I participated in the JRC on commercial refrigeration appliances in which resource efficiency aspects have been proposed for ecodesign (Ardente et. al, 2015).

Additional sets of experiments on air conditioning, ventilation and different combinations of services would also contribute to consolidate the method and to provide general conclusions on design variables of HVAC systems. Thus, even though the method has been developed and tested only for the design of heating systems, it could also be extended to support all HVAC systems, and possibly generalised to any other type of system for which product policy data are available. Future work could also focus in the robustness of the method and systematic sets of experiments on various HVAC systems to extract the main drivers of design for system optimisation.

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